

1    **Pyroclastic Flow Deposits on Venus as Indicators of Renewed Magmatic Activity**

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3    Bruce A. Campbell, Gareth A. Morgan, Jennifer L. Whitten

4    Center for Earth and Planetary Studies

5    Smithsonian Institution, MRC 315, PO Box 37012

6    Washington, DC 20013-7012

7    Phone: (202) 633-2472; E-mail: [campbellb@si.edu](mailto:campbellb@si.edu)

8

9    Lynn M. Carter

10    Lunar and Planetary Laboratory

11    1629 E University Blvd.

12    University of Arizona

13    Tucson, AZ 85721-0092

14    [lmcarter@lpl.arizona.edu](mailto:lmcarter@lpl.arizona.edu)

15

16    Lori S. Glaze

17    NASA Goddard Space Flight Center, Code 690

18    Greenbelt, MD 20771

19    [lori.s.glaze@nasa.gov](mailto:lori.s.glaze@nasa.gov)

20

21    Donald B. Campbell

22    Cornell University

23    Dept. of Astronomy, 502 Space Sciences Bldng.

24    Ithaca, NY 14853

25    [campbell@astro.cornell.edu](mailto:campbell@astro.cornell.edu)



26    **MAJOR POINTS**

- 27    •    **We map deposits on Venus formed by collapse of volcanic eruption columns.**
- 28    •    **Radar properties suggest the deposits are made up of coarse clastic debris.**
- 29    •    **The radar-bright material is currently being eroded by Venus subareal processes.**
- 30    •    **We propose that these deposits mark sites of renewed magmatic activity.**



**Abstract.** Radar-bright deposits on Venus that have diffuse margins suggest eruptions that distribute debris over large areas due to ground-hugging flows from plume collapse. We examine deposits in Eastern Eistla, Western Eistla, Phoebe, and Dione Regiones using Magellan data and Earth-based radar maps. The radar-bright units have no marginal lobes or other features consistent with viscous flow. Their morphology, radar echo strength, polarization properties, and microwave emissivity are consistent with mantling deposits comprised of few-cm or larger clasts. This debris traveled downhill up to ~100 km on modest slopes, and blanketed lava flows and tectonic features to depths of tens of cm to a few meters over areas up to  $40 \times 10^3 \text{ km}^2$ . There is evidence for ongoing removal and exhumation of previously buried terrain. A newly identified occurrence is associated with a ridge belt south of Ushas Mons. We also note radar-bright streaks of coarse material west of Rona Chasma that reflect the last traces of a deposit mobilized by winds from the formation of Mirabeau crater. If the radar-bright units originate by collapse of eruption columns, with coarse fragmental material entrained and fluidized by hot gases, then their extent suggests large erupted volatile ( $\text{CO}_2$  or  $\text{H}_2\text{O}$ ) amounts. We propose that these deposits reflect the early stage of renewed magmatic activity, with volatile-rich, disrupted magma escaping through vents in fractured regions of the upper crust. Rapidly eroding under Venus surface conditions, or buried by subsequent eruptions, these markers of recently renewed activity have disappeared from older regions.



## INTRODUCTION

Volcanic deposits dominate the landscape of Venus. At least three quarters of the planet is comprised of smooth plains with volcanic dome fields, coronae, and shield volcanoes. Most of these units are associated with morphologies such as lobate flow fronts, channel and levee structures, and pit-like or linear vents. Their surface roughness, as inferred from radar backscatter strength and polarization properties, is consistent with that of Hawaiian basalts of the pahoehoe to a'a types [Campbell and Campbell, 1992]. With the exception of "pancake" domes and narrow channels (canali) of enormous length, there are few features that have no obvious terrestrial parallel.

One type of deposit not explained by simple flow emplacement exhibits strong radar echoes, diffuse margins, and a lack of internal lobes or channels. These features have been identified on volcanoes in Dione Regio [Keddie and Head, 1995], on corona margins in western Eistla Regio [Campbell and Clark, 2006], and surrounding hybrid volcano-tectonic features near Sappho Patera in eastern Eistla Regio [McGill, 2000] (Fig. 1). All authors suggest some type of pyroclastic or ignimbritic process to explain their distribution and radar scattering properties. A very different type of landform at Scathach Fluctus, suggested to be an ignimbrite-like deposit by Ghail and Wilson [2013], has distinct lobate margins more similar to those of lava flows than the diffuse margins of the units studied here. To date, there has been no subsequent effort to examine the radar-bright, diffuse-margined deposits as a group, search for additional occurrences, and consider the implications of their stratigraphic position.

Work based on Venus Express VIRTIS data shows 1.02- $\mu\text{m}$  emissivity enhancements interpreted as evidence for recent (though of indeterminate age) eruptions [Smrekar et al., 2010]. These sites include Hathor and Innini Montes, two of the Dione Regio volcanoes noted as having radar-bright, diffuse-margin summit deposits. In contrast, Ushas Mons has neither enhanced 1.02- $\mu\text{m}$  emissivity nor radar-bright summit material. This correlation suggests a potential role of the radar-bright terrain in creating the infrared emissivity anomalies.

Radar measurements are the primary method of investigating the surface properties of Venus. The data used here come from the Magellan orbital radar mission and Earth-based radar mapping. Magellan collected near-global image coverage, in one sense of radar



polarization (horizontal transmit, horizontal receive), with about 100-m spatial resolution. Between radar mapping bursts, Magellan measured the microwave thermal emission from the surface, which is related to the dielectric permittivity and small-scale roughness of the terrain [Pettengill et al., 1992; Campbell, 1994]. The spatial footprint of the emissivity measurements is 20-30 km in the latitude range studied here, though the global gridded dataset is resampled at a 4.6-km posting. The radar-bright units studied below span at least two emissivity footprints along their N-S and E-W axes.

Earth-based radar mapping can achieve 1-2 km spatial resolution, and measure echoes in both the opposite-sense (OC) circular polarization and the same-sense circular (SC) mode. The OC echoes are very similar to Magellan measurements, and are strongly modulated by slopes that face toward the radar. The SC echoes are much more sensitive to small-scale surface roughness than to topographic slopes. We can also form the circular polarization ratio ( $CPR=SC/OC$ ), which allows for simple comparisons with rough surfaces on the Earth. The utility of these data were demonstrated in mapping of fine debris in the Venus highlands [Campbell et al., 2014; Whitten and Campbell, 2016], and we now have co-registered coverage of the side of Venus that faces Earth at inferior conjunction from 1988, 2012, and 2015 (the relevant part of which is shown in Fig. 2).

In this work, we further document the locations, physical properties, planform, and stratigraphic position of radar-bright deposits with diffuse margins, using Magellan data for high-resolution mapping and Earth-based data, where available, for polarimetric analysis. These analyses are used to constrain the stratigraphy and spatial scale of emplacement with respect to geologic setting. Finally, we discuss the implications of our results for plume collapse models, recent and future studies of infrared surface emissivity, and the inference of ongoing volcanic activity.

## LOCATIONS AND PROPERTIES OF RADAR BRIGHT UNITS

*Eastern Eistla Regio.* Campbell and Clark [2006] noted occurrences of radar-bright material with diffuse margins in eastern Eistla Regio, many on the western flank of Pavlova Corona (units P1 to P3, Figs. 3-4). Two other nearby deposits are associated with a densely ridged area (unit R1) and with an unnamed small corona southwest of Pavlova



(unit C1). The units have wispy or diffuse margins, moderate to very high backscatter coefficients, and appear to cover pre-existing volcanic and tectonic features. In their central regions there may be no distinguishable features, but closer to the margins the outlines of buried lava flows, graben, or fractures emerge from a thinning cover. Similar properties are associated with a unit on the southwest flank of Didilia Corona, and in each case the radar-bright materials appear to have moved downhill from corona margins or ridged terrain (Fig. 5). A topographic profile through Unit P3 shows that the bright materials cover a distance of about 100 km over slopes no larger than  $\sim 0.3^\circ$  (Fig. 6). The total area covered by this single unit is about 7,600 km<sup>2</sup>.

Two locales (northern unit P2 and southeastern unit D1) have prominent patterns of radar-dark streaks, which we infer to be fine-grained material moved by the wind onto the radar-bright materials [Greeley et al., 1992]. On unit D1, the dark material has moved westward (the direction of the prevailing wind at the surface) from a 65-km diameter volcanic edifice with a radar-dark summit region. The radar-bright unit covers the west flank of this volcano, so the wind streaks must reflect ongoing aeolian mantling of unit D1 (Fig. 5). It is interesting that such a small volcano summit region supplies the required volume of streak material, perhaps implying a fine-grained, localized pyroclastic deposit. In the case of northern unit P2, the streaks form a roughly radial pattern suggesting a source to the north, but their orientation is nearly orthogonal to the prevailing wind (Fig. 7).

The most dramatic remote-sensing property of these units is their high radar backscatter strength. Within Eastern and Western Eistla Regionēs the deposits have echoes stronger than any edifice-related lava flows: backscatter coefficient or “sigma-zero” values at  $\sim 46^\circ$  incidence angle are about -9 dB for unit P3. Such backscatter coefficients imply either (1) rough terrain (expressed as either a continuous topographic profile or a field of discrete objects) at the scale of the radar wavelength, or (2) an enhanced Fresnel reflectivity due to an increase in the real permittivity of the materials. The 12.6-cm wavelength, horizontal-polarized emissivity,  $E_H$ , for radar-bright units near Pavlova and Didilia are 0.80 to 0.85 at incidence angles around  $44^\circ$ . These values correspond to a dielectric permittivity,  $\epsilon'$ , range of about 3 for a plane surface to about 6.5 (similar to bare rock) for a surface that is rough at the wavelength scale [Campbell,



1994]. Most of the bright units have slightly higher  $E_H$  values relative to the surrounding flows, which is consistent with a higher degree of wavelength-scale roughness rather than an increase in permittivity. For comparison, the mean emissivity value for Venus is 0.845, and high-elevation regions of Maxwell Montes have typical values of  $\sim 0.3$  due to surface-atmosphere chemical reactions [Pettengill et al., 1992].

Absent enhanced reflectivity, the high radar backscatter values must come from significant roughness, expressed as the rms height/slope of either a continuous rough profile or a field of discrete objects, on the 12.6-cm horizontal scale. The necessary rms height/slope would be comparable to that of terrestrial a'a flows, or to a field of clasts with diameters up to at least about 4 cm [Campbell, 2002]. The lack of any obvious structure (at the few-hundred meter scale) within the deposits suggests a blanket of clastic debris that is always the locally highest stratigraphic unit. The actual size-density distribution of the clasts cannot be determined; there may be a sorting process during emplacement that leaves larger rocks close to the vent or deposits them preferentially at the base of a downslope deposit. The presence of wind streaks would suggest clast sizes toward the smaller end of the range in those locales, since the fine-grained windblown material would not easily cover more rugged terrain.

*Western Eistla Regio.* The two major hybrid volcano-tectonic constructs of Western Eistla Regio, Anala Mons and Irnini Mons (with Sappho Patera at its summit), have large, radar-bright deposits with diffuse margins emanating radially and extending downslope from their corona-like, densely ridged annuli [McGill, 2000] (Figs. 8-9). A profile through Unit I1 shows that the area of continuous bright material covers about 70 km from a point on the Irnini Mons flank, and extends onto nearly flat terrain to the north (Fig. 10). The average slope of the Irnini flank in this area is  $1.2^\circ$ . The margins of units I1, I2, and A1 are uncertain where they meet the densely fractured terrain, but there is some evidence that diffuse deposits extend onto the floor of Sappho Patera. The contacts between the floor units and the radar-bright terrain are poorly defined, and it is difficult to determine whether there is embayment by the lava flows or exhumation of these flows by erosion of the mantling debris. Very thin streaks, inferred here to form by aeolian movement of fine material, on the radar-bright units, and subtle diffuse patterns



overlapping dark flows just inside the dense fracture belts are more consistent with the latter scenario. A minimum area for the bright deposits around Anala (Units I1 and I2) is about 41,000 km<sup>2</sup>. Radar brightness (the average sigma-zero value for central unit I1 is -9.7 dB at 45° incidence angle) and emissivity properties for unit I1 are similar to those observed in Eastern Eistla Regio.

The northwestern portion of unit I1 shows that the mantling unit thickness must be a few meters or more to cover flows with central channels as well as lobate margins high enough to produce a glint from the radar-facing slope (Fig. 11). This view illustrates the apparent erosion of the mantling material in the dense pattern of linear streaks, trending north-northwest, and the patchy brighter areas on the radar-dark flow to the northwest. There are also areas of darker radar signature within units I1 and I2. We infer that these may be localized areas where the initial deposit was thin, which seems unlikely for a surge deposit traveling such distances, or that subsequent breakdown of the coarse material has begun to remove the mantle.

Unit I3 is anomalous among radar-bright deposits noted thus far (Fig. 12). It is situated in a topographic low of a region characterized by both plains-forming (broad with indistinct or non-lobate margins) and edifice-derived (narrow with lobate margins) flows (Fig. 9). The deposit mantles tectonic fractures and ridges, as well as a moderate-backscatter flow complex from the southwest. There is no evident direction of transport, and the margins are a collection of linear “spines” that parallel the local tectonic fabric. At no point along its margin does unit I3 appear to be embayed by a later flow. It also lies just beyond the farthest extent of flows that emerge from the margin of unit I1, so we cannot make a stratigraphic connection from that relationship. We suggest that I3 is an erosional remnant of a once larger I1 deposit, perhaps protected to some degree by its location in the lowest local topography. This would be consistent with the “spiny” appearance that suggests formation (and perhaps aeolian removal) of fine material by erosion of the original rocky mantle.

These observations confirm the inferences from Pavlova and Didilia Coronae that the radar-bright, diffuse deposits are superposed on all other geologic features. Even more than in those instances, the deposits at Irnini Mons suggest substantial removal of clastic mantling material by breakdown of the rocks and redistribution of resulting fines by the



wind. While they are thus stratigraphically “young”, the diffuse deposits have undergone a considerable degree of weathering. The rate of that breakdown might be high under Venus conditions [Fegley et al., 1997].

*Dione Regio.* Keddie and Head [1995] present a detailed analysis of volcanic stratigraphy for the major edifices within Dione Regio (Figs. 1-2). They note radar-bright, diffuse-margin material near the summits of Hathor and Innini Montes, and perhaps on Nepthys Mons. Only near the summit of Innini Mons does the radar-bright signature appear to arise in part from altitude dependent surface-atmosphere effects on the dielectric permittivity. They further note that these materials blanket underlying features, including lava flows and tectonic features such as graben, and infer a pyroclastic or ignimbrite style of emplacement. Dione Regio is the only major location of radar-bright, diffuse terrain within the Earth-based radar coverage (Fig. 2), and our combined data from 1988, 2012, and 2015 offer a view of polarimetric scattering behaviors (Fig. 13) at a signal-to-noise ratio much higher than that available to Keddie and Head [1995].

We note multiple areas of radar-bright units with diffuse margins on Hathor and Innini Montes, but nearby Ushas Mons appears to have no major instances of this type of deposit (Fig. 13a). Those on Innini Mons are relatively concentric to the cluster of radar-bright domes on the summit, while those on Hathor Mons extend away from an oval summit region toward the north and west. We also note a large (maximum dimensions of ~230 km on NW-SE axis, ~100 km SW-NE), radar-bright feature along the densely fractured terrain south of Ushas Mons that appears to superpose the ridge structure and some extensional features. This large radar-bright unit has not been previously discussed, perhaps due to its location away from the major edifices and gaps in Magellan image coverage.

Topographic profiles (Fig. 14) show that the radar-bright material south of Ushas Mons extends ~70 km from a modest topographic high east of the ridge belt. In both profiles the western extent of the deposit occurs near or within a local depression. The local slope, dipping to the west, is only about  $0.14^\circ$  along the northern transect, while the southern transect has what might be (extrapolating through the data gap) up to about a  $0.3^\circ$  slope at its eastern edge. The area of the bright deposit is about 21,000 km<sup>2</sup>.



In both the Magellan image and the Earth-based SC data, the ridge-related material is very bright (an average sigma-zero value of -10 dB at 33° incidence angle), suggesting a high degree of surface roughness (Fig. 15). The circular polarization ratio, which is sensitive to the degree of scattering by wavelength-scale roughness, shows enhanced values for the radar-bright units on Hathor Mons and the ridge-belt area (Fig. 13b). The deposits near the summit of Innini Mons are only modestly enhanced. The ridge-belt feature and the bright deposit on the west flank of Hathor Mons have CPR values of 0.4 to 0.5 at incidence angles around 40°. These values are consistent with the upper range of few-cm to decimeter-scale roughness for basaltic flows on the Earth [Campbell, 2009], and stand out markedly against the background of lower CPR values for the plains- and edifice-forming flows. As with the radar-bright deposits in Eistla Regio, there is no evidence of the low microwave emissivity expected if these brightness changes came from an increase in the Fresnel reflectivity.

Keddie and Head [1995] noted that Nepthys Mons, formed on the north flank of a ridge belt, has a 40-km diameter region of enhanced radar echoes near its highest elevation. The SC image shows an oblong region of enhanced echoes in the same region, though the strength of this echo with respect to the surrounding flows is not as distinguishing as those on Hathor Mons or the ridge belt south of Ushas Mons (Fig. 16). Some parts of the radially fractured flanks of Mielikki Mons might be mantled by radar-bright material, but the SC echo shows only modest enhancement across the whole edifice (Fig. 17). Finally, one site noted in the VIRTIS study of Smrekar et al. [2010] but not visible in the Earth-based coverage, Idunn Mons (Fig. 18), may have radar-bright, diffuse material on the northwestern parts of its summit, but even at the full resolution of the Magellan images we cannot confirm the mantling relationships evident in other locales.

*Phoebe Regio.* Rona Chasma is part of the long rift zone of Phoebe Regio, trending roughly SW-NE in our study locale (Fig. 19). Associated with the rift zone are numerous volcanic flow fields. Centered on 0.5° S, 286° E is a field of radar-bright streaks extending about 60 km along a SE-NW axis (Fig. 20). The streaks occur on a patch of volcanic plains with very low radar backscatter that appears to be the oldest rift-related



flow unit superposing the regional plains. These very smooth flows are superposed by radar bright (i.e., rougher) flow fields from fractures on the western side of Rona Chasma. Where the radar-bright streaks meet the later flows, the margins of those flows are less distinct than elsewhere, suggesting that the streak material has banked up against the flow lobes. In at least one locale (noted on Fig. 20), a streak crosses over a flow and causes an increase in the radar echo. This shows that the streaks form by redistribution of coarse, clastic debris rather than by removal of a regolith cover to expose the rock beneath [e.g., Greeley et al., 1992].

The streak materials appear to have traveled from NW to SE, which is not consistent with the prevailing wind pattern. Even if they were oriented from east to west, it is unlikely that the Venus surface winds can mobilize such large particles. A plausible scenario is that these streaks formed as a result of winds associated with the formation of the 23.8-km diameter crater Mirabeau (Fig. 19). The center of Mirabeau (1.1 N, 284.3 E) is about 260 km from the farthest extent of the streaks, which trend nearly radial to the crater. Figure 21 presents the likely sequence of events in this region, with the inference that the streaks are the remnants of a once-contiguous deposit that may have extended eastward to the fractures of Rona Chasma.

## DISCUSSION AND IMPLICATIONS

The existence of radar-bright deposits with diffuse margins in a few locations on Venus has been known since initial mapping efforts [Keddie and Head, 1995; McGill, 2000; Campbell and Clark, 2006]. Our work shows that these deposits comprise moderate-scale units along fractures near the summits of classic shield volcanoes like Hathor and Nepthys Montes, and perhaps Mielikki and Idunn Montes. Similar deposits are related to densely fractured terrain south of Ushas Mons, the flanks of Pavlova and Didilia Coronae, and surrounding the hybrid volcano-tectonic features Anala and Irnini Montes. The radar-bright streaks near Rona Chasma may likewise have once extended to the outer fractures of this rift zone.

In the larger occurrences, we find evidence for mantling of pre-existing lava flows and tectonic features by clastic debris up to several meters thick, which thins and perhaps is sorted to finer particle sizes downslope of the highest elevations. We also note evidence



for erosion of this material, exhumation of flow features, and isolated outliers that implies larger initial extents. The smaller occurrences exhibit some of these attributes, but often have less enhanced SC radar echoes; we speculate that these deposits are older, or were not as initially extensive or thick, such that subsequent erosion has left less distinct traces. In most cases there is no clear evidence for embayment of the mantling deposits by later flows, so they are the locally youngest units except for radar-dark wind-streak material. Only near Rona Chasma do we infer significant superposition of radar-bright, clastic material by lava flows, and here the debris is confined to streaks aligned with winds from the Mirabeau impact.

These deposits of clastic material are clearly ephemeral, since they are typically observed only at the top of the local stratigraphy rather than interleaved with the flows that make up the other deposits from the ridge belts or volcano summits. The bright streaks west of Rona Chasma are a rare glimpse of an older deposit preserved on early flows from the major regional source, and the total amount of material is small with respect to the inferred initial coverage. We conclude that the clastic debris is most often a recent volcanic phenomenon in each area, where the “recent” term can only have a quantitative meaning if the rate of erosion is known.

Smrekar et al. [2010] modeled the surface emissivity at 1.02  $\mu\text{m}$  from VIRTIS data and Magellan topography, and found some degree of enhancement from Idunn, Meilikki, Hathor, and Innini Montes; no such signature was noted for Ushas Mons. The first-order correlation with the enhanced backscatter signatures might suggest that the radar-bright material plays a role, perhaps due to grain size or compositional properties, in modulating the 1.02  $\mu\text{m}$  emissivity. An issue with this interpretation is that the modeled emissivity (Fig 2B of Smrekar et al. [2010]) does not suggest enhancement from the large radar-bright unit on the ridge belt south of Ushas Mons. If the radar-bright units are of generally similar composition and particle size, then the lack of correlation in 1.02- $\mu\text{m}$  properties between the Hathor Mons summit and the ridge-belt unit suggests little sensitivity of the modeled emissivity to these youngest materials.

It is unlikely that, given the density of the lower atmosphere, that fallout from a lofted plume could emplace such extensive, clastic deposits [Fagents and Wilson, 1995; Wilson and Head, 1981; Carter et al., 2006]. A more plausible mechanism for significant (10s of



km) lateral transport, especially of coarse particles, is plume collapse, where a low (up to a few km), volatile-driven column creates an outer ring of cooler material falling away from the peak rise altitude [Thornhill, 1993; Campbell et al., 1998; Glaze, 1999]. A linear chain of vents on Venus would be even more effective than circular vents, for the same eruption rates, in producing such collapsing columns, and thus pyroclastic flows [Glaze et al., 2011]. This mechanism is also more consistent with the asymmetric distribution of mantling material downhill of its sources at volcano summits or in the densely fractured terrain. At the Magellan image resolution of  $\sim 100$  m, we cannot further pursue characterization of the possible vent geometries.

If our interpretation of a generally thin mantling layer of coarse debris is correct, then the closest terrestrial comparisons are low aspect ratio features like the Taupo ignimbrite (dated to  $\sim 186$  CE). From a strictly morphologic perspective, the parallels with the large radar-bright unit south of Ushas Mons are striking. Total range from the vent for the Taupo deposit is  $\sim 80$  km, the volume is about  $30 \text{ km}^3$  over an area of about  $20,000 \text{ km}^2$ , and there is few-cm scale clastic debris [Wilson, 1985; Dade and Huppert, 1996]. The Venus example covers around  $21,000 \text{ km}^2$ , extends 70-100 km, has inferred thickness as little as 10's of cm to a meter (i.e., a volume of  $21 \text{ km}^3$  for a constant 1-m depth), and is characterized by clast sizes of perhaps a few cm.

Highly silicic eruptions like Taupo are not expected on Venus based on existing compositional data. There is evidence, however, of terrestrial basaltic eruptions that produce deposits of similar morphology. Two such units were identified by Williams [1983], with the larger covering an area of  $1200 \text{ km}^2$ . The dense, hot atmosphere of Venus may create significant differences in how clasts are entrained and transported, allowing emplacement over greater distances. Large explosive eruptions have also been linked with the Columbia River Basalt province [Brown et al., 2014], supported by models of volatile accumulation and explosive events in such ancient flood basalt eruptions [Glaze et al., 2017].

Even the smaller units mapped here, assuming they were originally up to a few meters thick, imply a substantial total mass of volatiles (concentrations of up to 5%  $\text{H}_2\text{O}$  or  $\text{CO}_2$ ) in the rising magma [Airey et al., 2015], and a chain of vents extending along the fractured terrain [Glaze et al., 2011]. In general, discharges of volatile-rich magma occur



during the early phases of a magma source's interaction with the surface. For example, fire-fountain activity was typical of the early stages of lunar mare volcanism. Subsequent eruptions were depleted of volatiles, yielding the more classic plains-forming lava flows. Due to this timing the largest surviving lunar pyroclastic deposits occur only in elevated regions (such as the Aristarchus Plateau) where the later flows did not cover them [Zisk et al., 1977].

Venus has a much more active cycle of magmatic activity, with the expectation of many batches of magma rising to the surface in any one region over time. Given their stratigraphic position and requirement for enhanced volatile content, the radar-bright clastic deposits may reflect the early phases of renewed magmatic activity. All of the occurrences are related to elevated, fractured terrain within regions of extensive volcanism, consistent with such new batches of magma contributing to uplift and extensional tectonism in an area. There is evidence for erosion and removal of the coarse-grained debris (perhaps quite rapid), so those we observe are only the thickest or youngest deposits. There may have been many more such deposits over time, each marking sites of renewed eruptive phases.

## CONCLUSIONS

We examine radar-bright deposits with diffuse margins in Eastern Eistla, Western Eistla, Phoebe, and Dione Regiones using Magellan data and Earth-based radar maps. The radar-bright units have no marginal lobes or other features consistent with viscous flow. Their morphology, radar echo strength, polarization properties, and microwave emissivity are consistent with extensive mantling deposits comprised of few-cm scale clasts. This coarse debris traveled downhill up to about 100 km on modest slopes, and blanketed pre-existing lava flows and tectonic features to depths of 10's of cm to perhaps a few meters. The coarse material thins with downhill distance from the highest elevations, and there is evidence for ongoing removal and exhumation of previously buried terrain. A newly identified occurrence lies astride a ridge belt south of Ushas Mons, mirroring a similar correspondence with densely fractured terrain in Eistla Regio. We also note radar-bright streaks of coarse material on lava flows west of Rona Chasma, and suggest that these reflect the last traces of an earlier, more extensive deposit that was



391 mobilized by winds from the formation of Mirabeau crater. If the radar-bright units  
392 originate by collapse of eruption columns, with coarse fragmental material entrained and  
393 fluidized by hot gases, then their extent and volume suggests large erupted volatile (CO<sub>2</sub>  
394 or H<sub>2</sub>O) amounts. We propose that these deposits reflect the early stage of recently  
395 renewed magmatic activity that supplies the volatiles and contributes to uplift and  
396 extensional tectonism in an area. Rapidly eroding under Venus surface conditions, or  
397 buried by subsequent volatile-poor eruptions, these markers of renewed activity have  
398 largely disappeared from older regions. Their short erosional timescale may offer new  
399 insights on surface chemical and aeolian processes. Future Earth-based observations and  
400 orbital missions could target these sites for evidence of crustal deformation or active  
401 eruptions. Future landed missions could better constrain the overall range of Venus  
402 surface composition as a guide to the volatile budget and physical properties of erupted  
403 material.

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412 RTLS/GBT-3-DELAYDOPPLER-V1.0, NASA Planetary Data System, 2016]. The 2015  
413 Venus data are being prepared for submittal to PDS under a grant from the NASA  
414 Planetary Observations Program. Images that use the multi-year composite data are  
415 provided on a Smithsonian open archive site: [https://airandspace.si.edu/research/data-](https://airandspace.si.edu/research/data-repository)  
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493



**Fig. 1.** A Magellan left-looking radar map labeled with locations of features noted in this study (approximate area 48 S to 25 N latitude, -85.5 E to 55 E longitude).

**Fig. 2.** Earth-based radar data summed from observations of the southern hemisphere in 1988, 2012, and 2015. Opposite-sense polarization (OCP) radar echoes, so echoes from areas closer to the center of the planet are much brighter. Approximate area 48 S to 11 S latitude, -85.5 E to -11 E longitude. Blurred region at upper left is due to radar echoes from Beta Regio that are “folded over” by the delay-Doppler imaging method.

**Fig. 3.** Regional (10.8N–16.0N; 35.3E–40.0E) view of radar bright deposits (outlined in orange) in the vicinity of Pavlova Corona. Magellan left-looking radar image data. Black line denotes trace of topographic profile in Fig. 5.

**Fig. 4.** Three-dimensional perspective view of the region shown in Fig. 3, based on Magellan image and altimetry data. View is from the south. Note downslope emplacement of labeled units away from corona rims and densely ridged terrain.

**Fig. 5.** View of the southwest flank of Didilia Corona, with a radar-bright, diffuse unit labeled D1; unit P2 from Fig. 3 is visible at lower right. Magellan left-looking radar image data, image area 15.5N-17.6N, 35.8E-38.4E. Note the pattern of dark streaks running west from the 65-km volcanic edifice at right center.

**Fig. 6.** Topographic profile of the southwest flank of Pavlova Corona, from 12.87 N, 36.79 E (left) to 13.90 N, 38.30 E (right). Vertical offset is in km from a reference radius of 6051 km. The radar-bright material of Unit P3 covers approximately 100 km from the corona rim. Data are from the Magellan GTDR dataset. Raw along-track footprint values are smoothed and gridded at a horizontal posting of 4.6 km. Vertical accuracy can be as fine as about 20 m over smooth terrain.

**Fig. 7.** Full resolution, Magellan left-looking radar view of wind streaks in northern part of radar-bright, diffuse unit P2 (lower left). Image width about 25 km; north at top. Note the outlines of lava flows emerging from the northwestern margin of the radar-bright deposit.

**Fig. 8.** Regional (9N–18N; 10E–22E) view of radar bright deposits (outlined in orange) on Irnini and Anala Montes. Magellan left-looking radar image data.

**Fig. 9.** Three-dimensional perspective view of the region shown in Fig. 8 based on Magellan image and altimetry data. View is from the north. Note downslope emplacement of units I1, I2, and A1 away from densely lineated rims. Unit I3 is isolated in the nearby plains.

**Fig. 10.** Topographic profile of the northern flank of Irnini Mons at 15.1 E longitude, running from 16.92 N at left to 14.70 N at right. Vertical offset is in km from a reference radius of 6051 km. The radar-bright material in this locale covers



approximately 70 km of the flank and adjacent flat terrain, but in other areas the deposit extends to 80-100 km. Data are from the Magellan GTDR dataset. Raw along-track footprint values are smoothed and gridded at a horizontal posting of 4.6 km. Vertical accuracy can be as fine as about 20 m over smooth terrain.

**Fig. 11.** Full-resolution, left-looking Magellan image of radar-bright, diffuse deposit northwest of Irnini Mons. Image width 188 km; north at top. Note the lobate flows that disappear southwards beneath the bright mantling unit (northern part of unit I1), and the dense streaks and residual patches that suggest ongoing erosion of the mantle and exhumation of the flows.

**Fig. 12.** Full-resolution, Magellan left-looking radar image of unit I3. Image width 120 km; north at top.

**Fig. 13a.** Earth-based opposite-sense circular (OC) radar image of Dione Regio [approximately 20.5 to 45 S latitude, 316 to 335 E longitude]; simple cylindrical projection. White arrows denote locations of radar-bright, diffuse deposits.

**Fig. 13b.** CPR color overlay on OC image of the same region shown in Fig. 11a. Note that CPR values in the ridge-belt region at center and some parts of the Hathor Mons deposits are 0.4 to 0.5, suggesting high few-cm scale roughness.

**Fig. 14a.** Magellan left-looking radar image of the radar-bright material south of Ushas Mons; area covered is 33 S to 28 S, 321 E to 326 E. White lines indicate locations of topographic transects in Fig. 14b. Gaps are due to missing data in the Magellan coverage.

**Fig. 14b.** Topographic profiles across the radar bright material south of Ushas Mons: (1) at 30.35 N, running from 321 E at left to 326 E at right; (2) at 31.04 N, running from 321 E at left to 326 E at right. Vertical offset is in km from a reference radius of 6051 km; profile (1) is offset by an additional 500 m for clarity. The radar-bright material covers ~70 km downhill of a topographic high just east of the ridged terrain. Data are from the Magellan GTDR dataset. Raw along-track footprint values are smoothed and gridded at a horizontal posting of 4.6 km. Vertical accuracy can be as fine as about 20 m over smooth terrain. Gaps are due to missing data in the Magellan coverage.

**Fig. 15.** Magellan left-looking radar image (top panel) of radar-bright materials astride a ridge belt south of Ushas Mons; (lower panel) Earth-based SC polarization image. Region shown is approximately 32.3 S to 28.6 S latitude, 322 E to 325.6 E longitude.

**Fig. 16.** Magellan radar image (top panel) of Nepthys Mons at center right, with Arecibo SC-polarization image (lower panel). Region shown is approximately 35 S to 31 S latitude, 313.5 E to 321 E longitude. Image width 780 km.



**Fig. 17.** Magellan left-looking radar image of Mielikki Mons, with Arecibo SC-polarization image of surrounding region as inset. Image width 422 km.

**Fig. 18.** Magellan left-looking radar image of Idunn Mons. Image width 195 km.

**Fig. 19.** Regional view from Magellan radar data of Rona Chasma and Mirabeau crater (23 km diameter). Image area approximately 1.7 S to 2.5 N latitude, 284 to 290 E longitude. Arrow notes region of radar-bright streaks on smooth plains unit.

**Fig. 20.** Magellan radar view of radar-bright streaks west of Rona Chasma. Image width 190 km. Black arrow notes location of brighter echo from lava flows where a streak crosses the lobe.

**Fig. 21.** Sketch maps showing the inferred sequence of geologic events west of Rona Chasma. (A) A smooth, radar-dark flow unit (black) from fractures along Rona Chasma floods a region of regional plains. (B) A deposit of clastic material (yellow) from the Rona Chasma fractures is emplaced on the smooth flows. (C) Rougher lava flows (red) superpose part of the clastic deposit, which is also eroding from its initial thickness and extent. (D) Mirabeau crater forms, and the resulting winds redeposit the remaining clastic material into streaks that bank against, and sometimes cross, the radar-bright lava flows.



Figure 1.



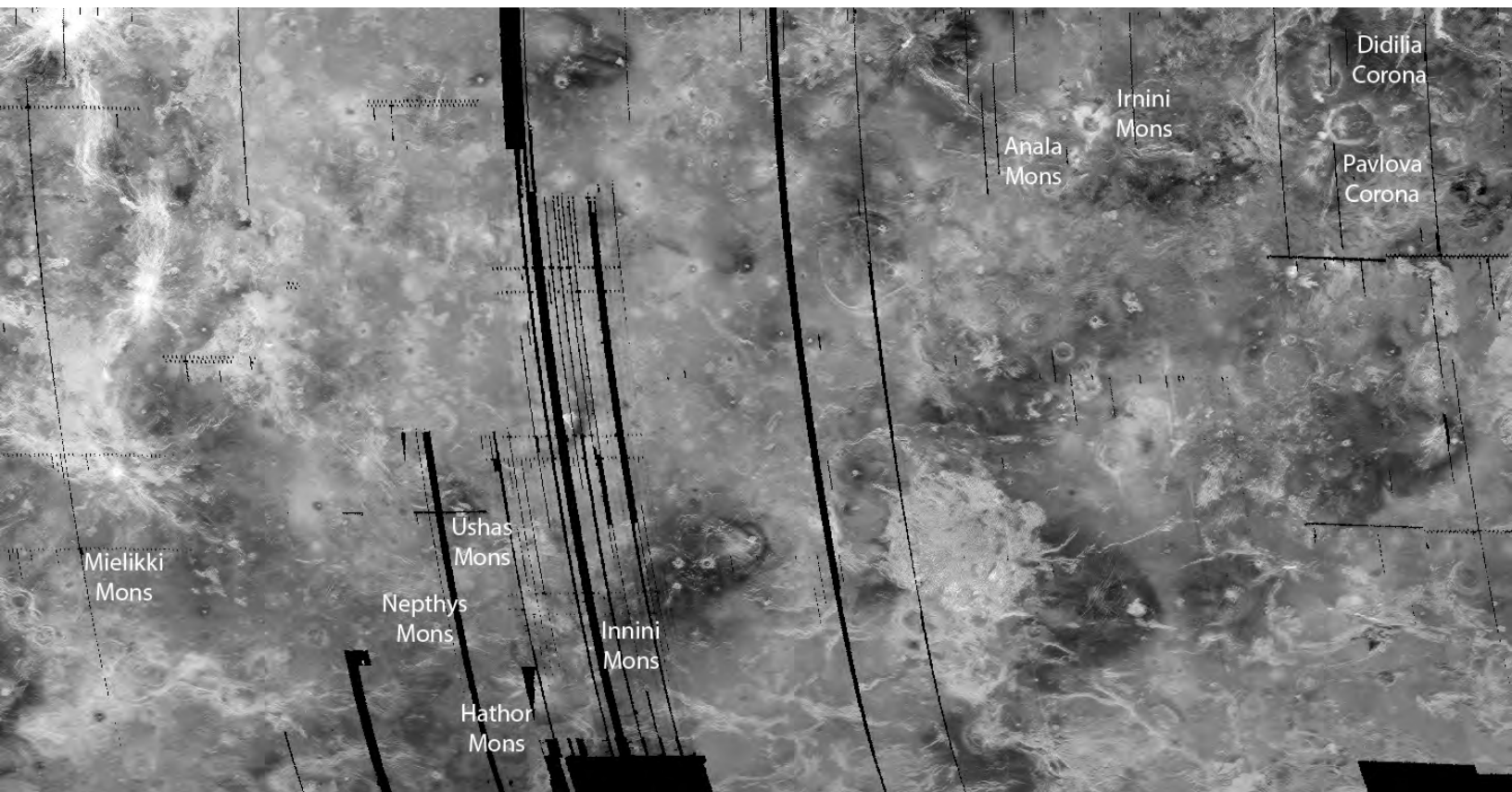




Figure 2.



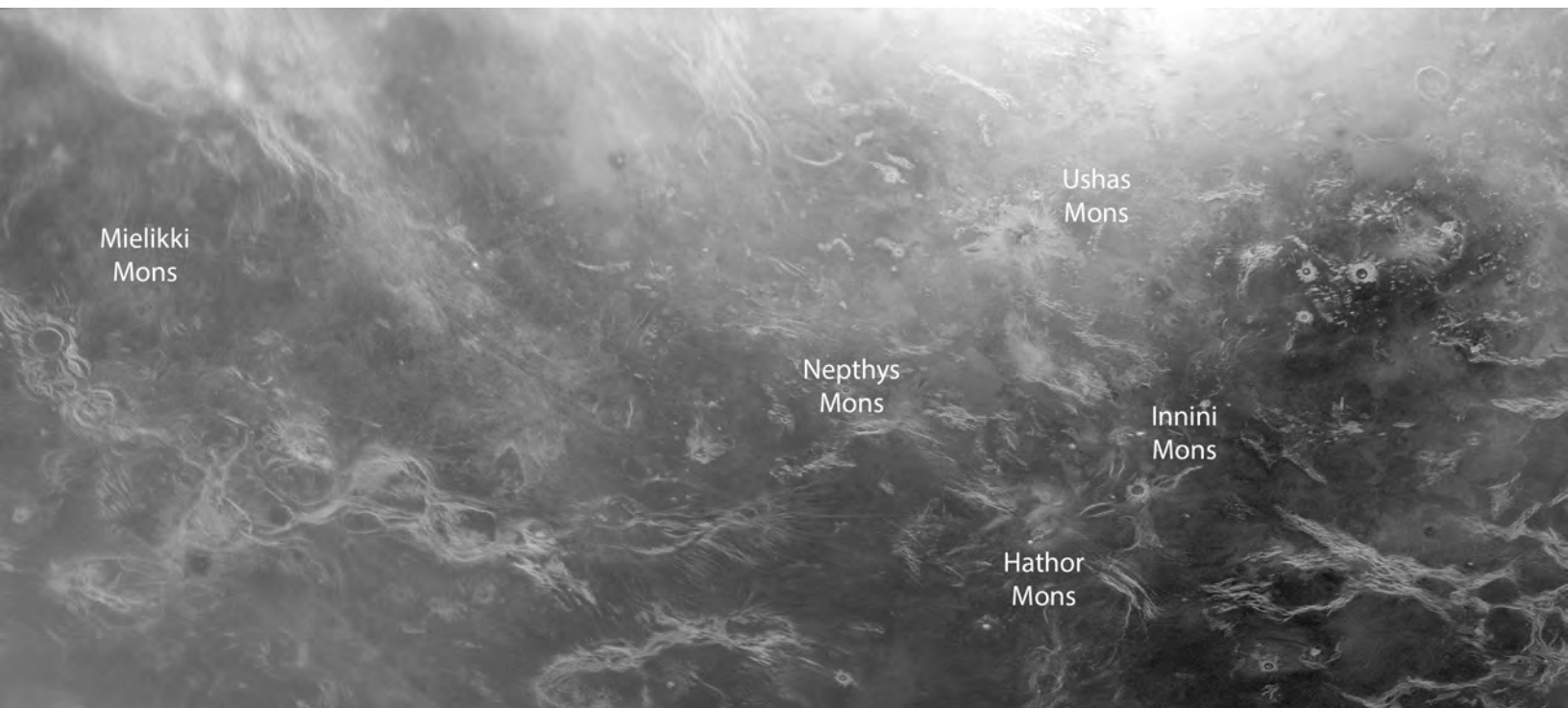
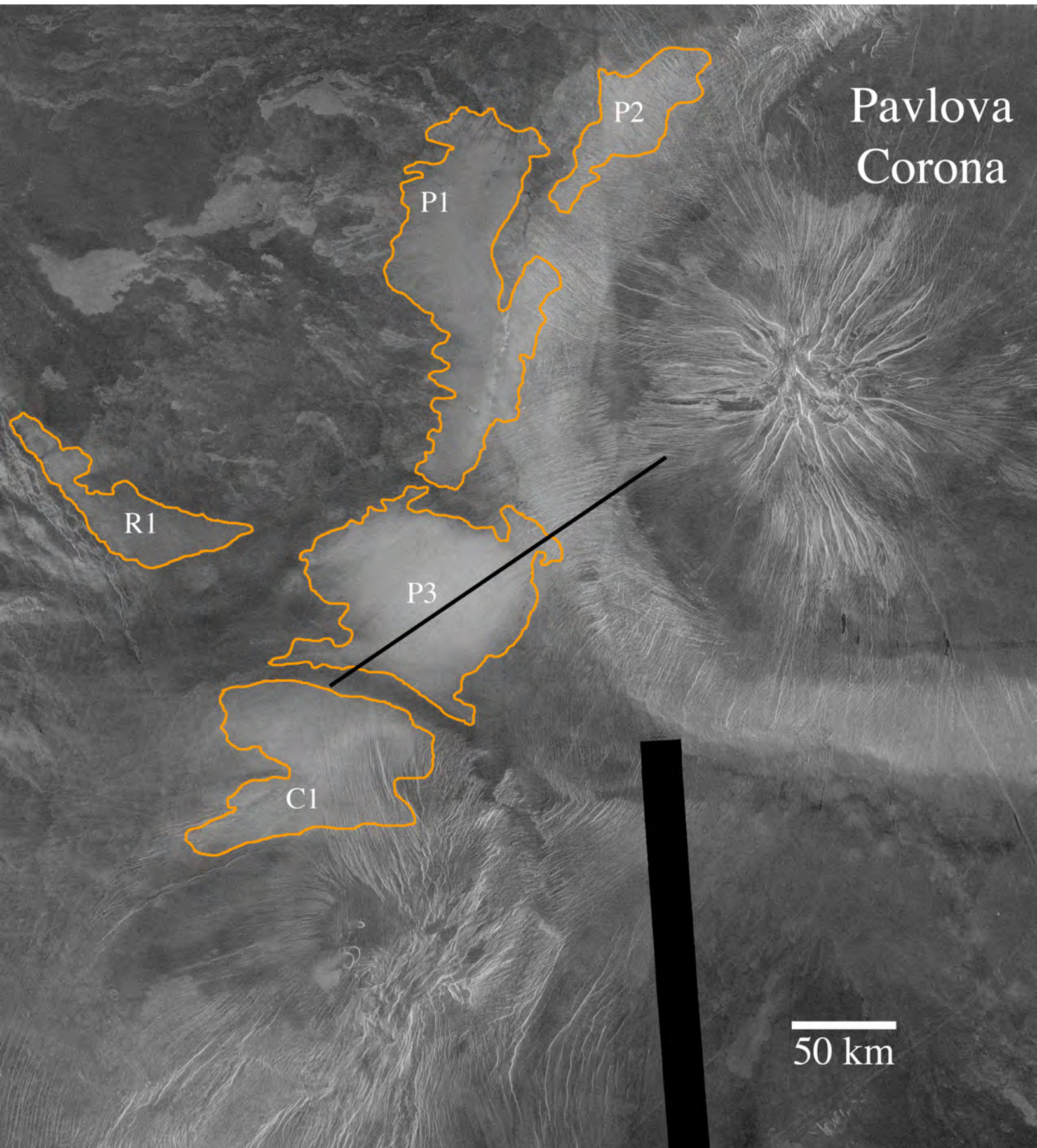




Figure 3.



# Pavlova Corona



50 km



**Figure 4.**



Pavlova  
Corona

P2

P1

R1

P3

C1

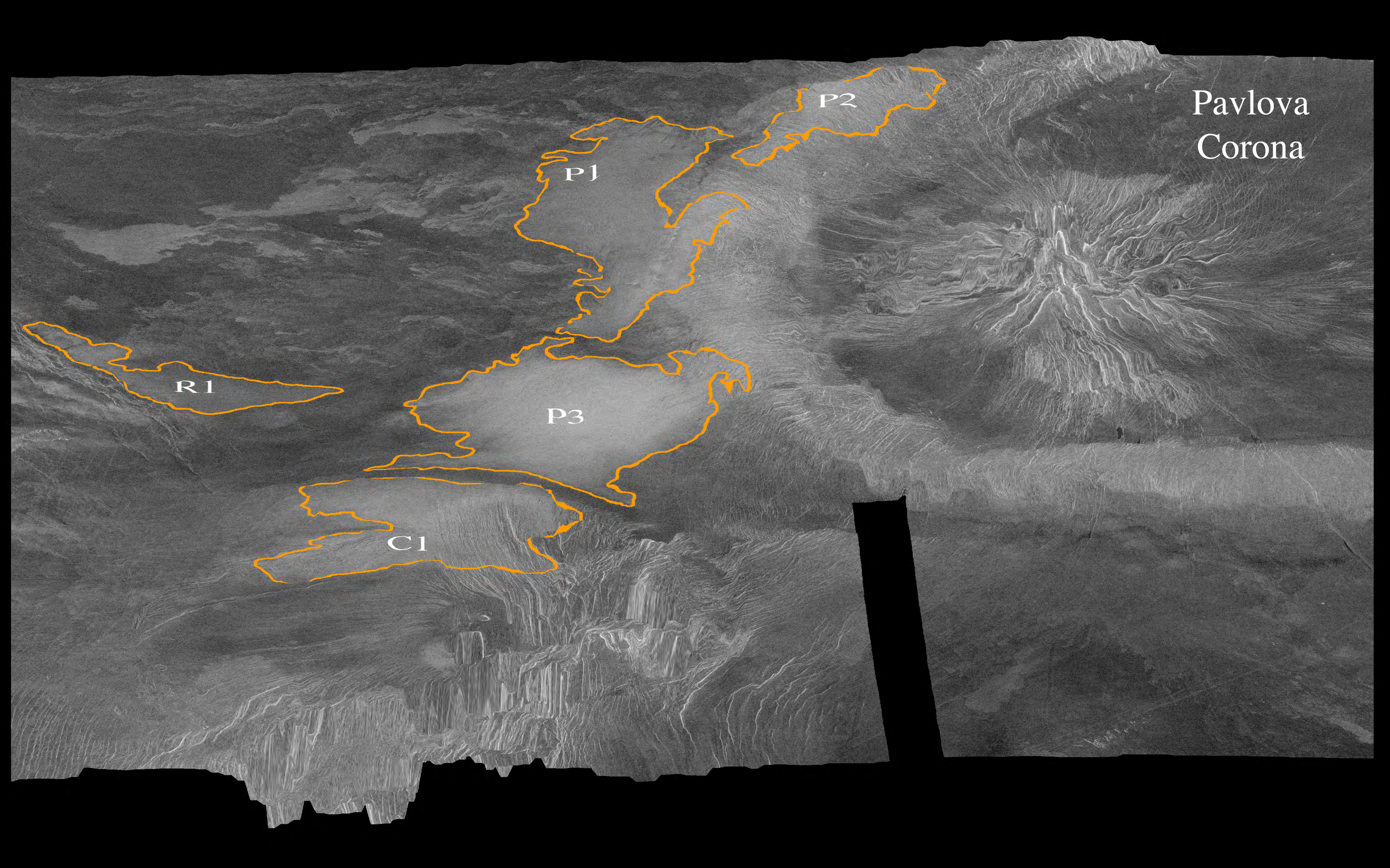




Figure 5.



# Didilia Corona

D1

50 km

P2

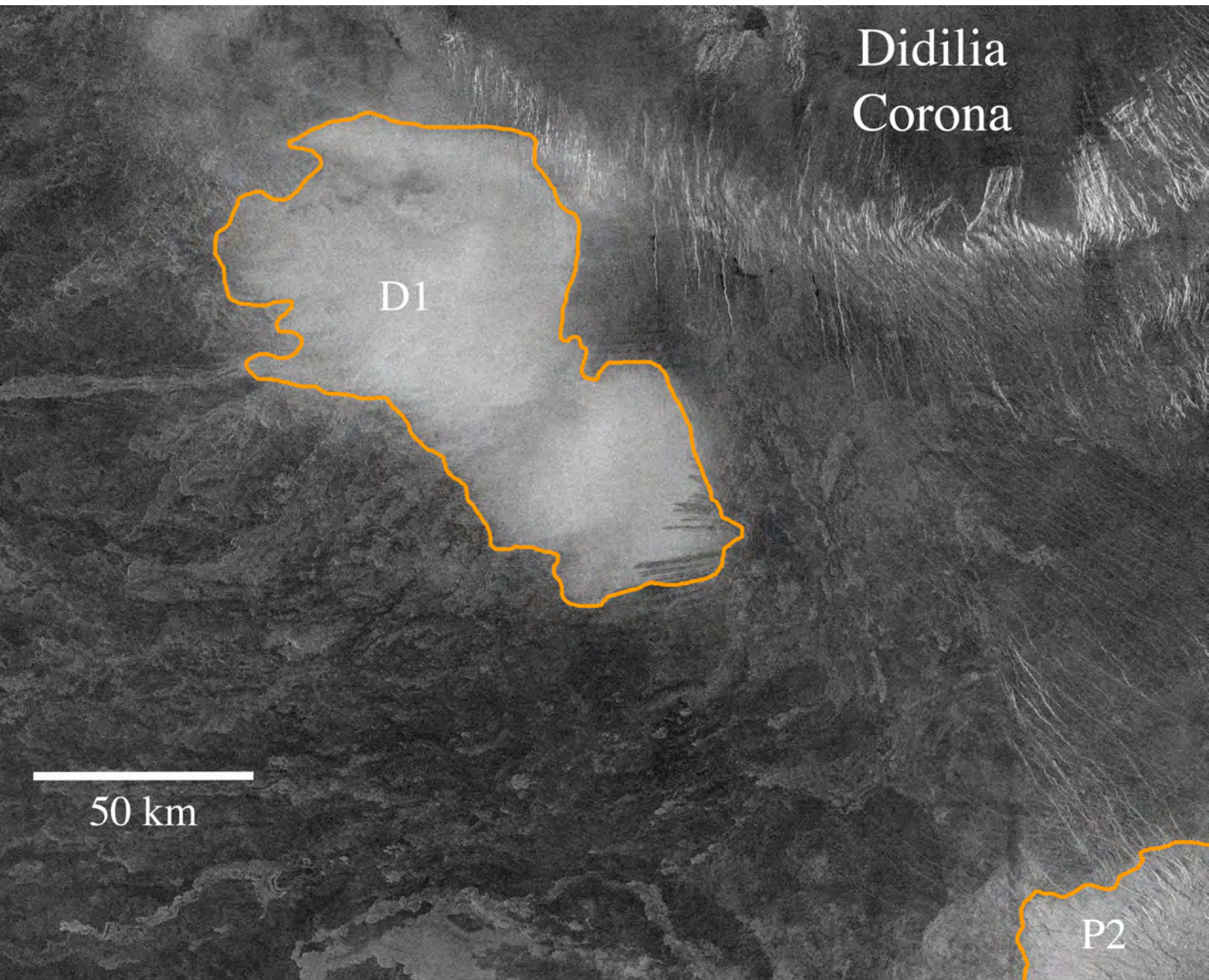
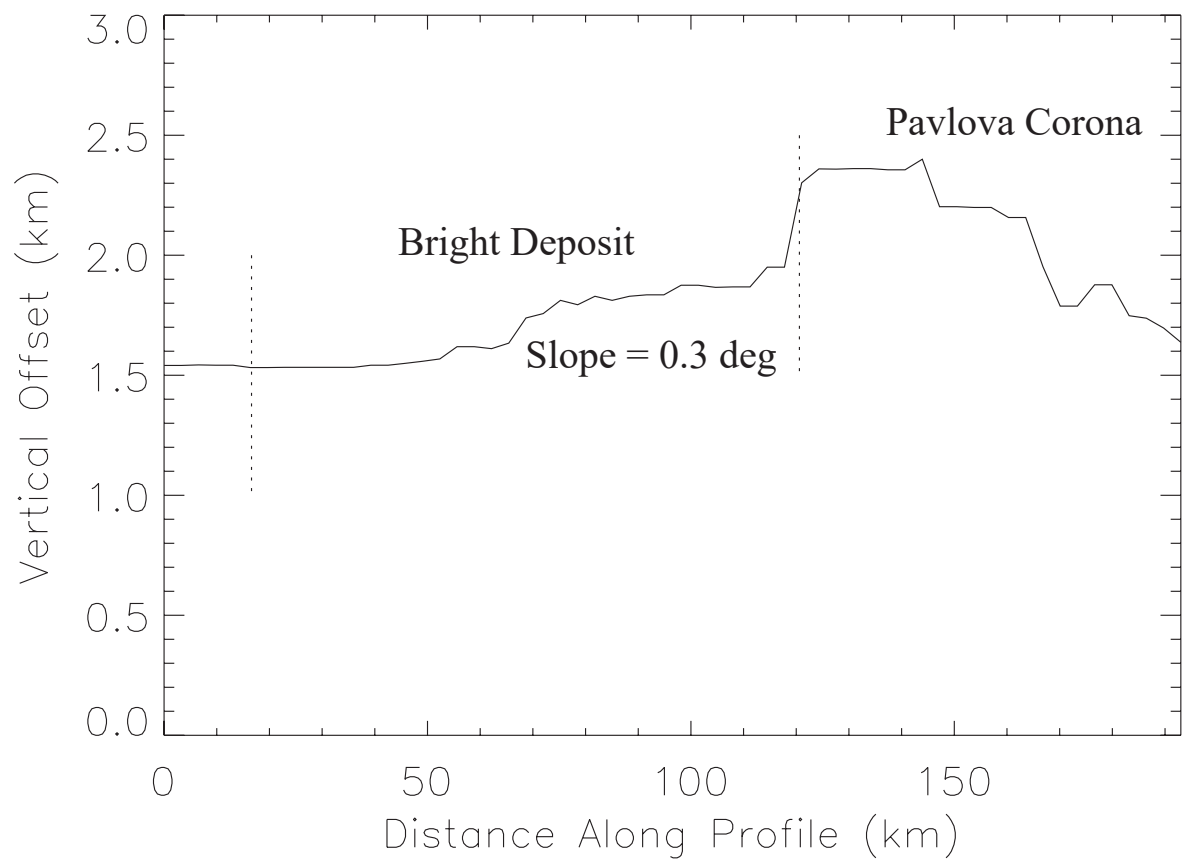




Figure 6.







**Figure 7.**



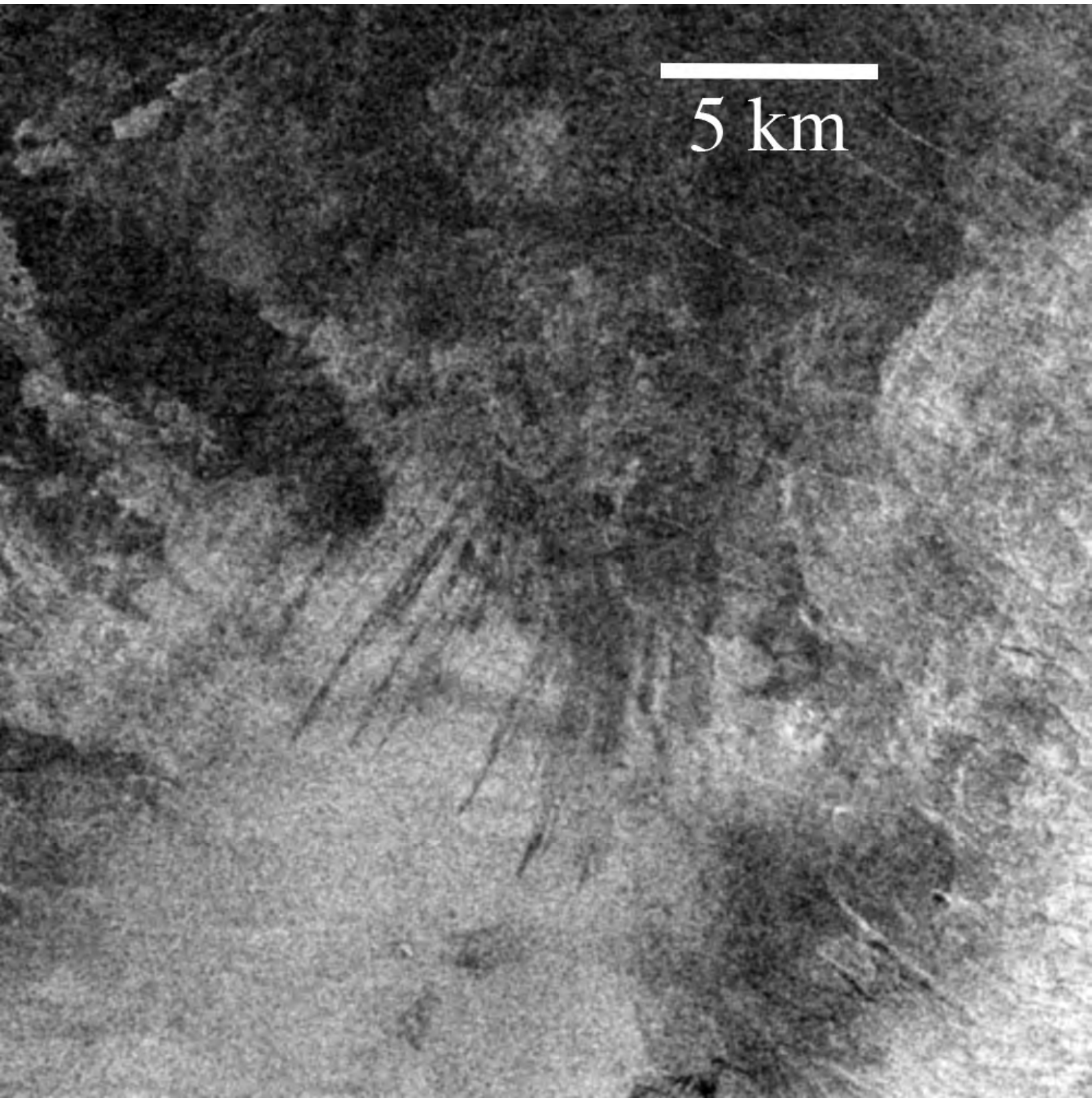
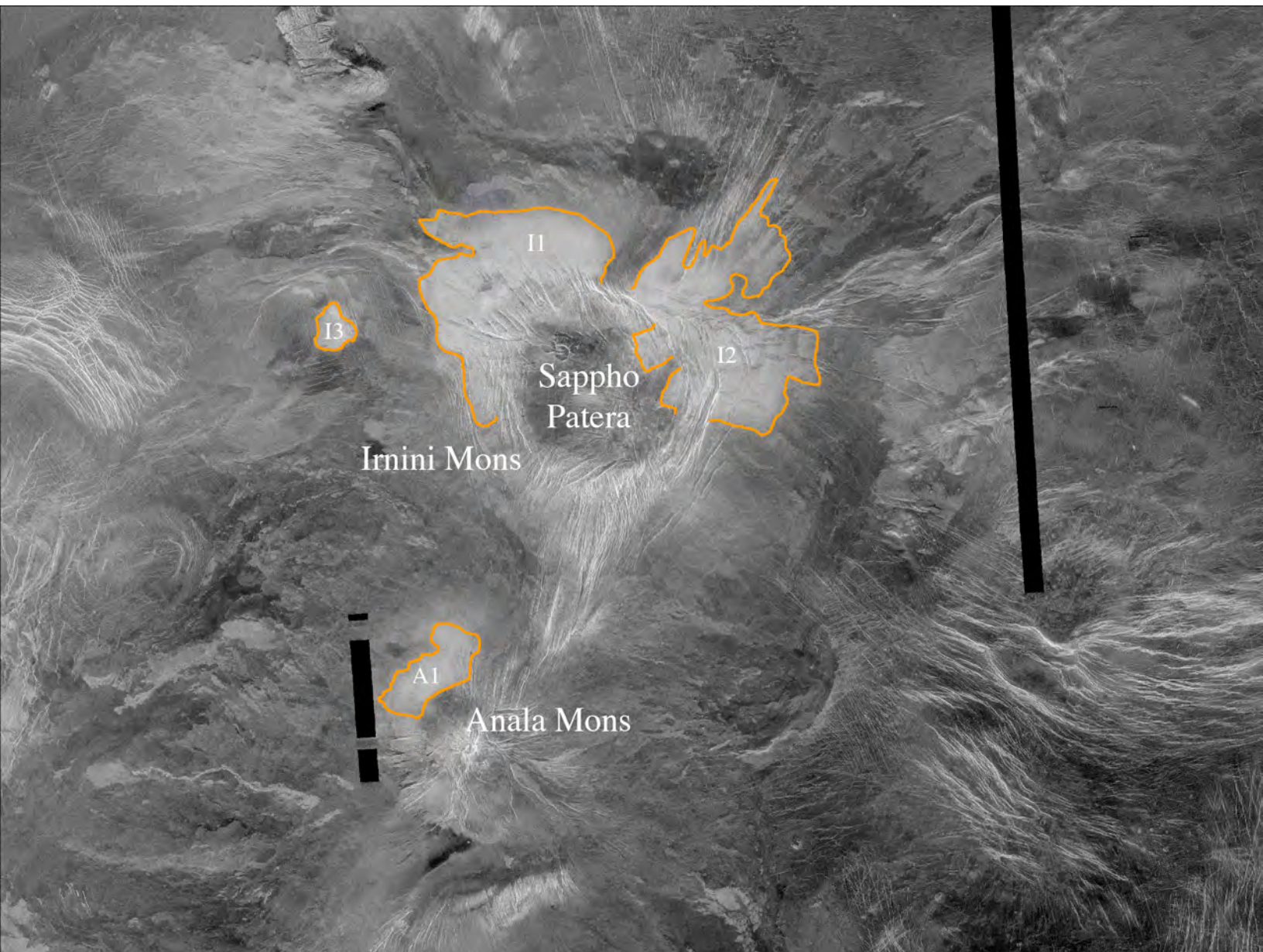




Figure 8.







**Figure 9.**



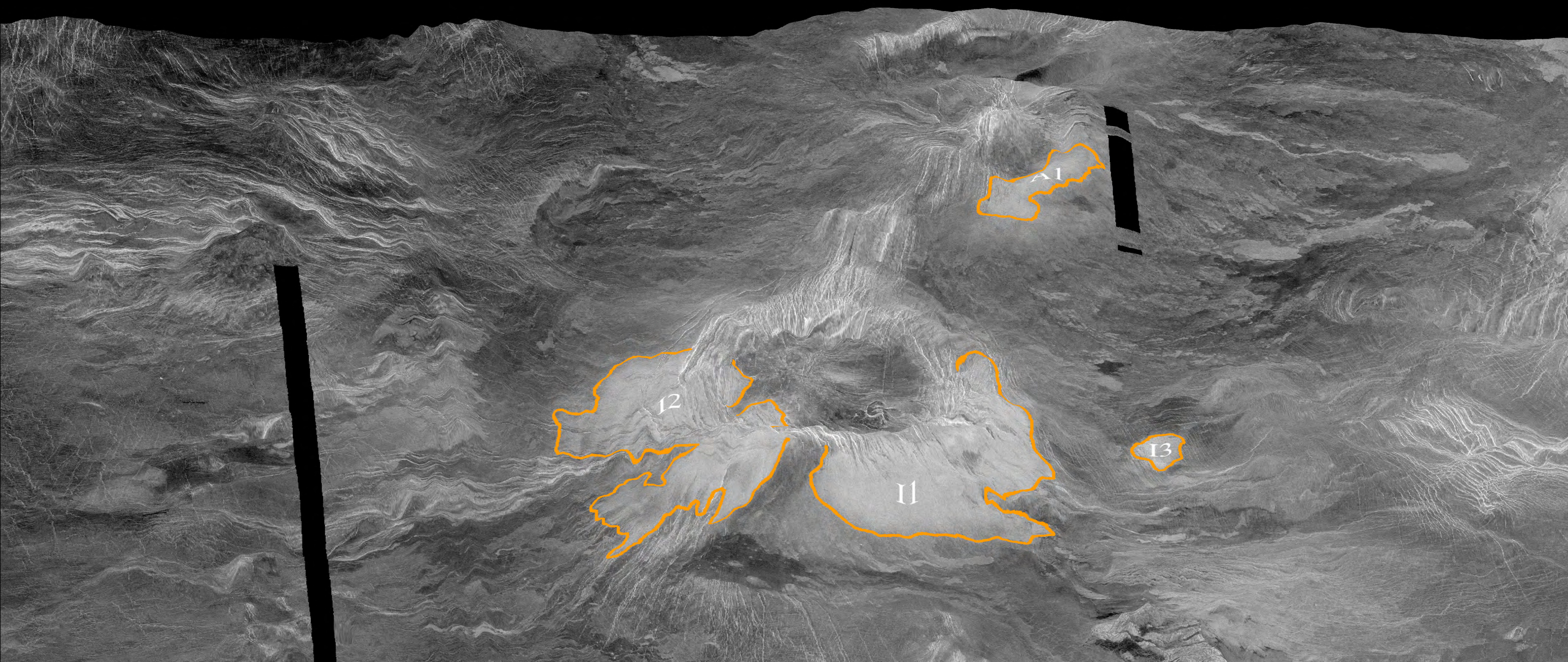




Figure 10.



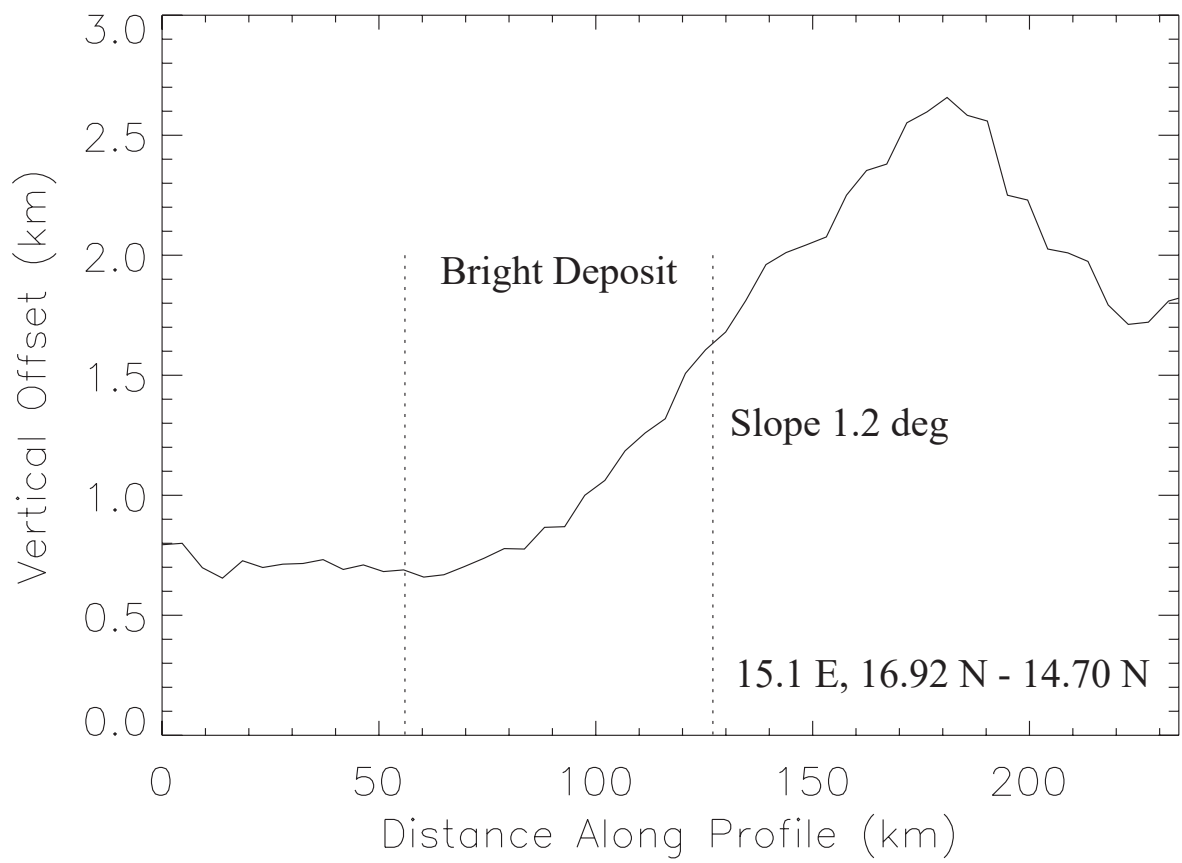




Figure 11.



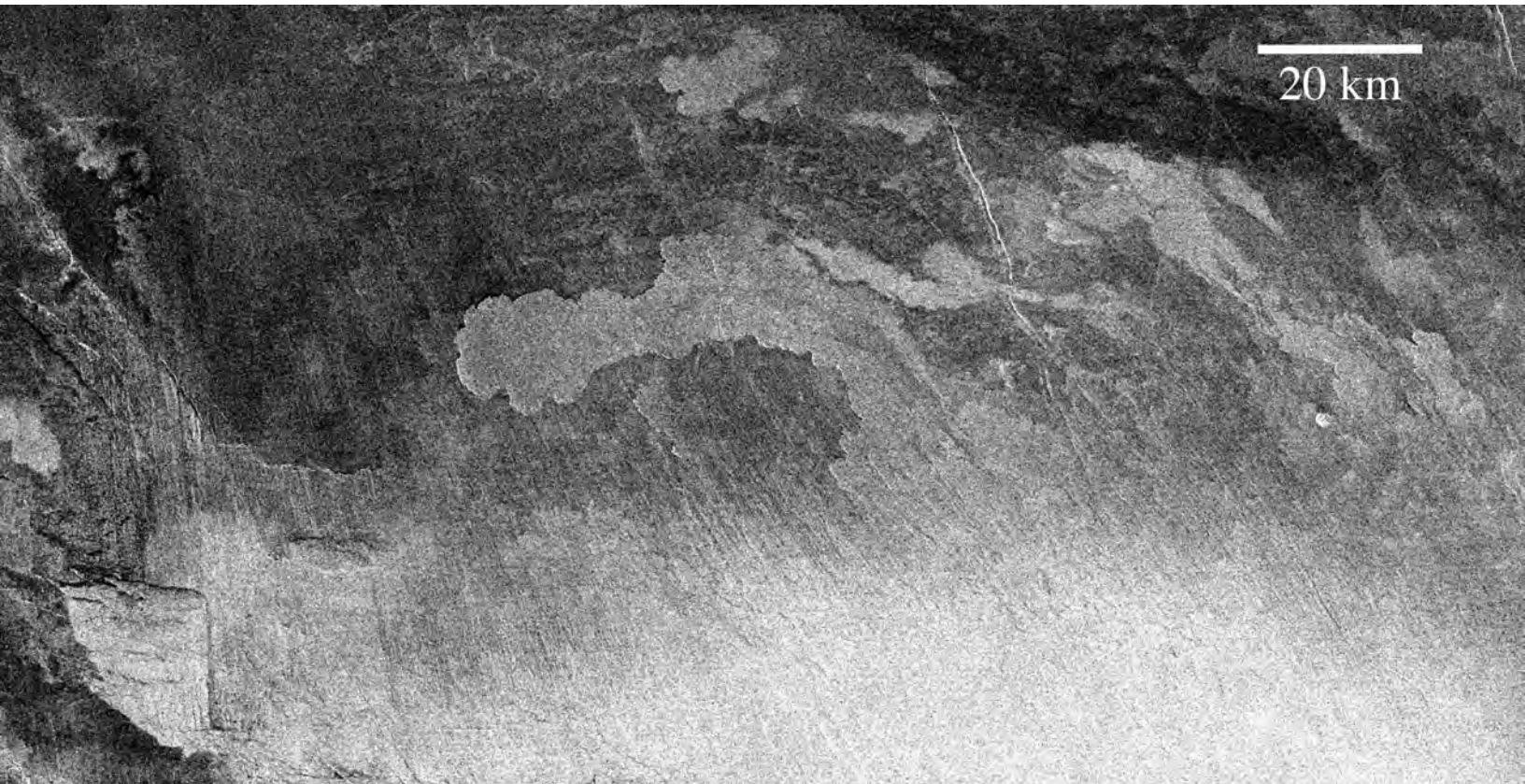
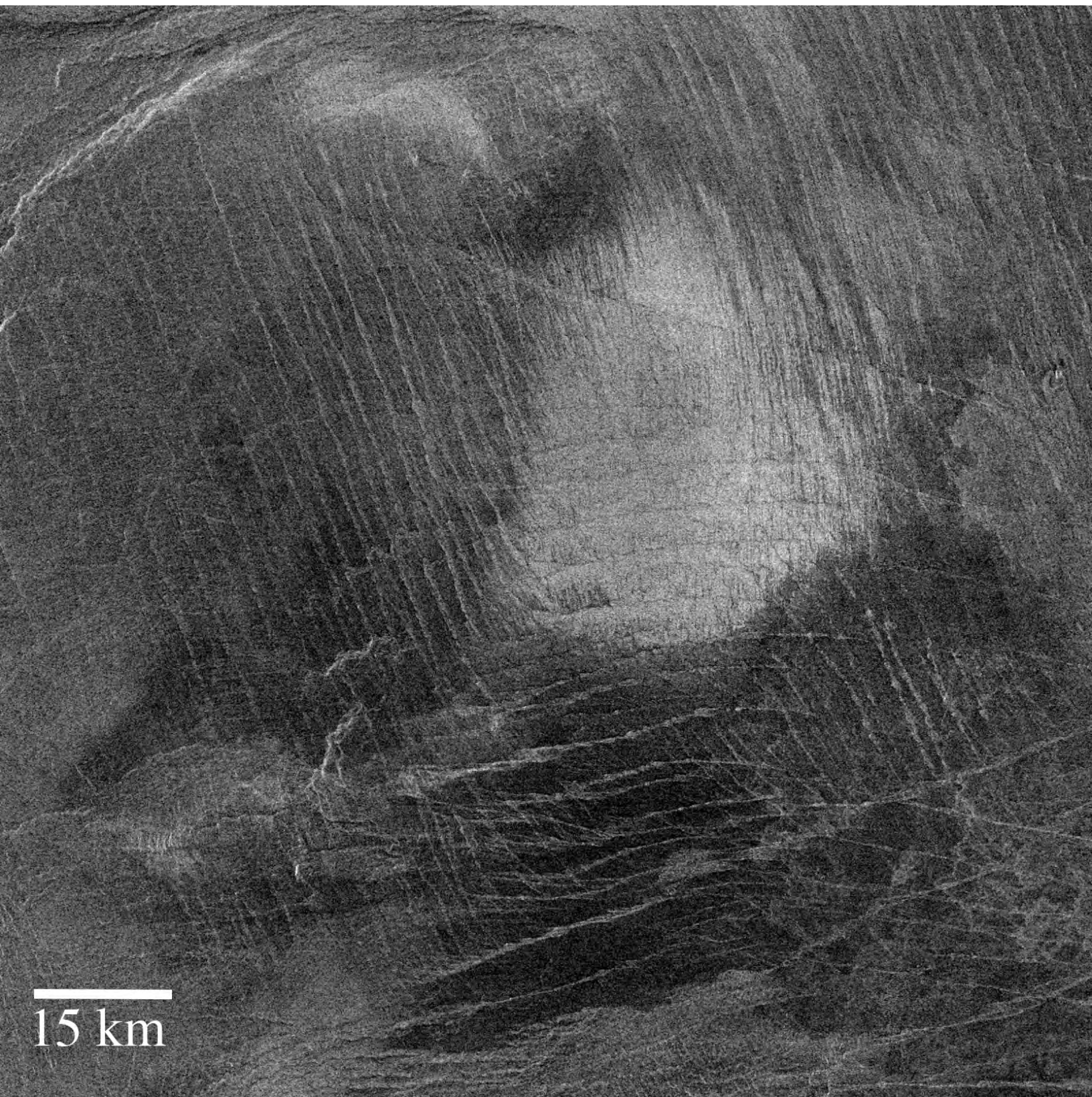




Figure 12.





15 km



Figure 13.



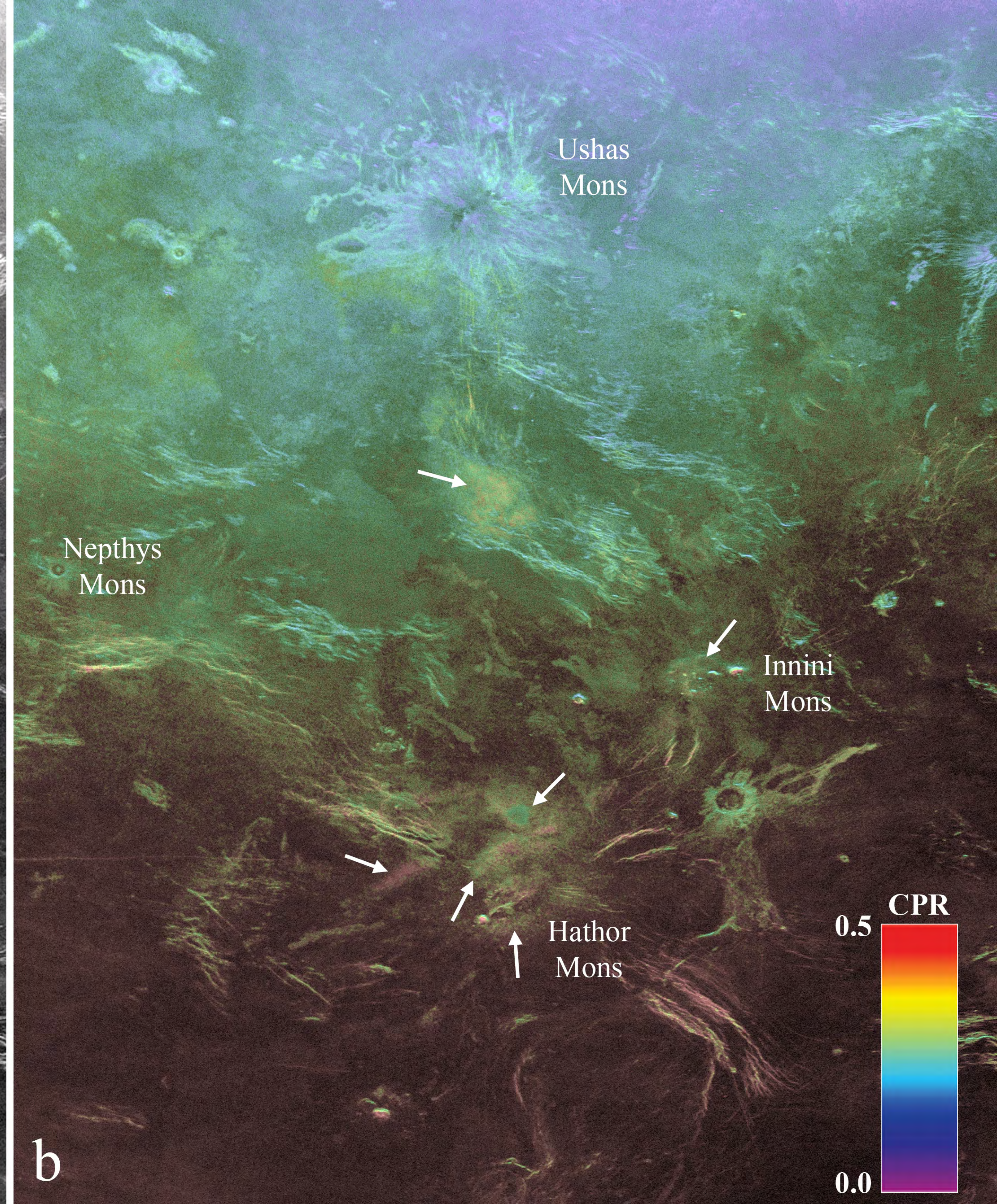
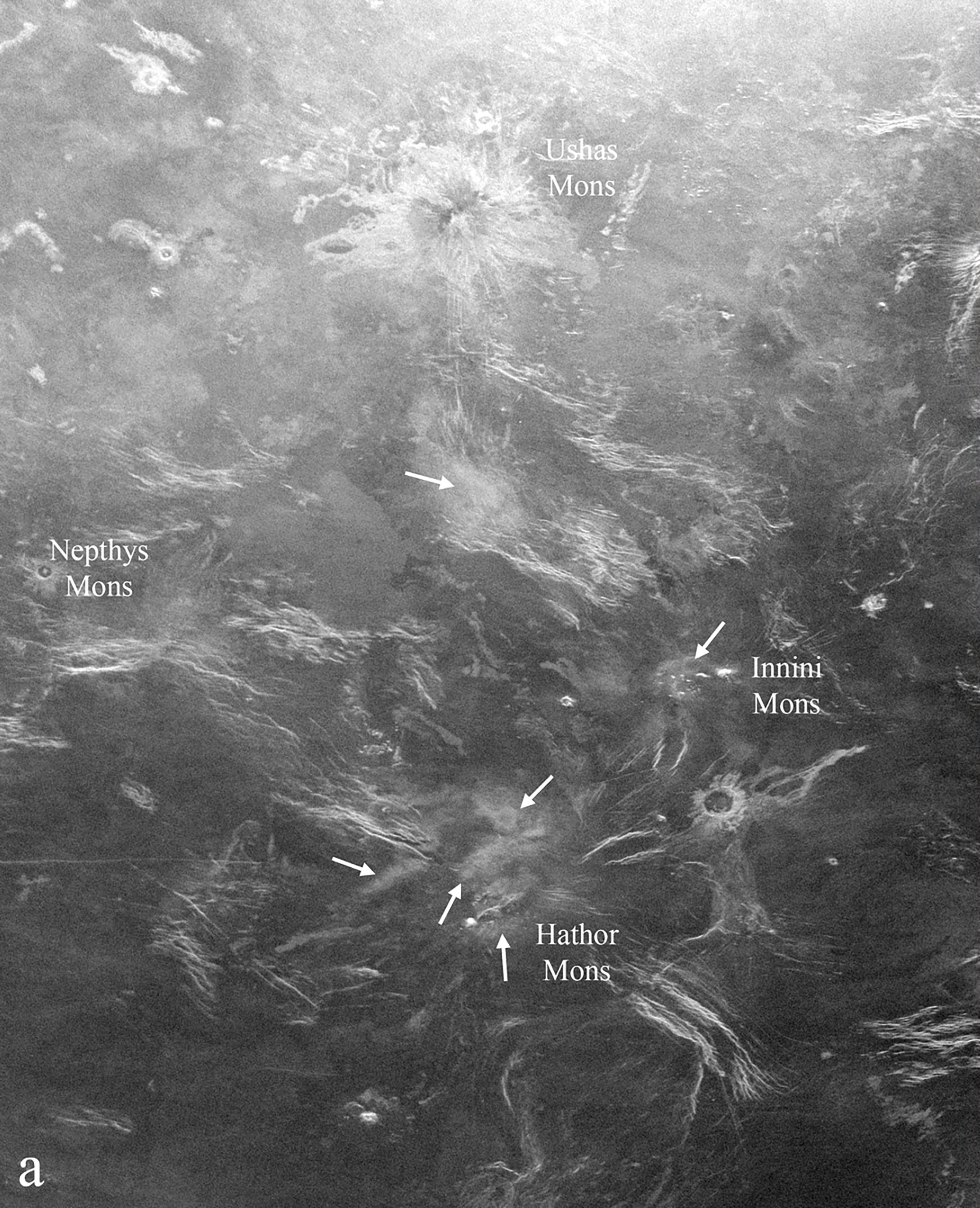




Figure 14.



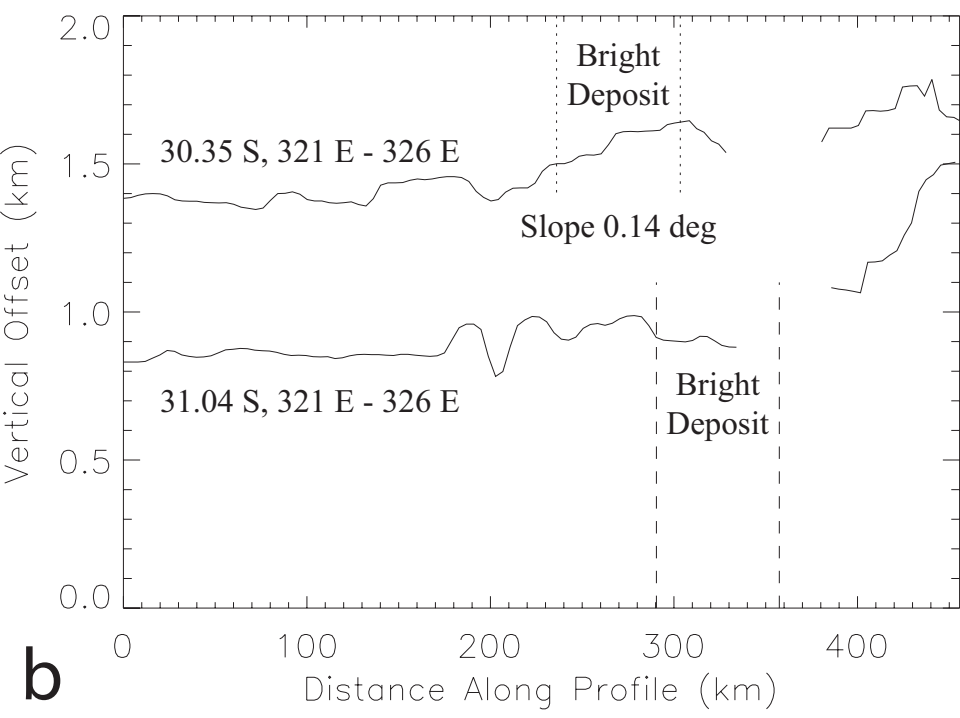
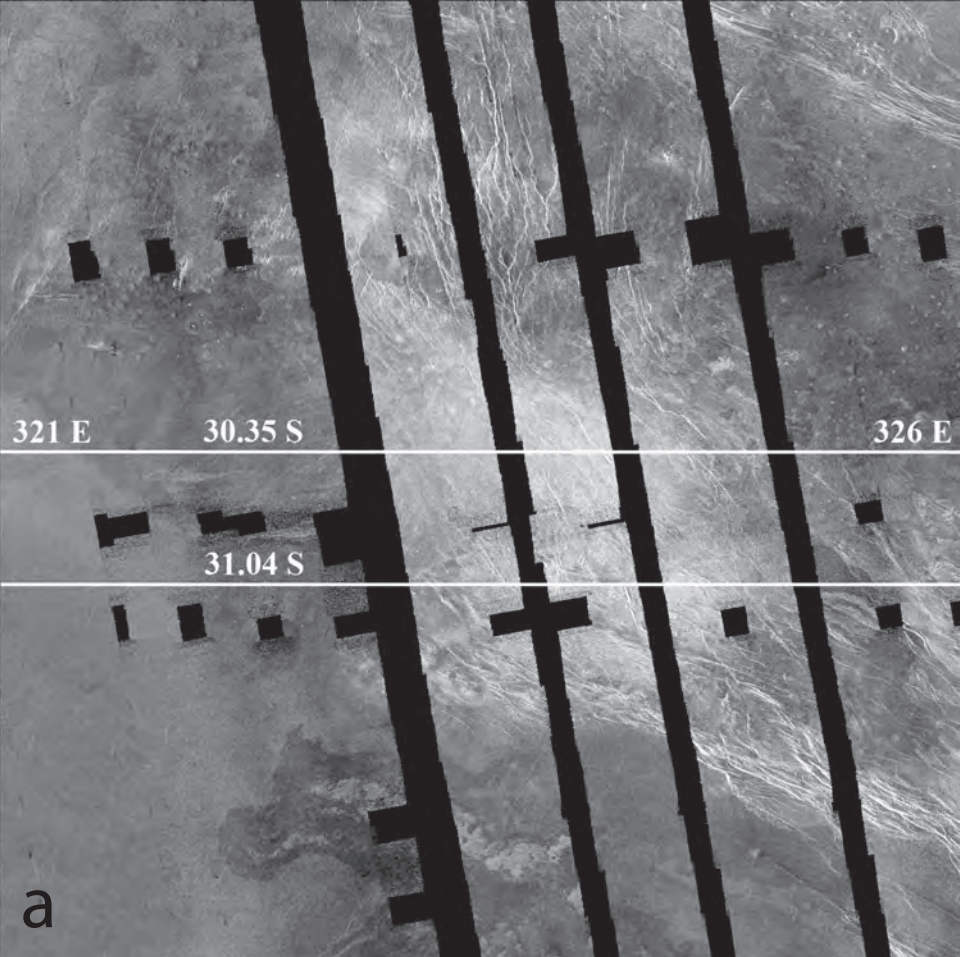
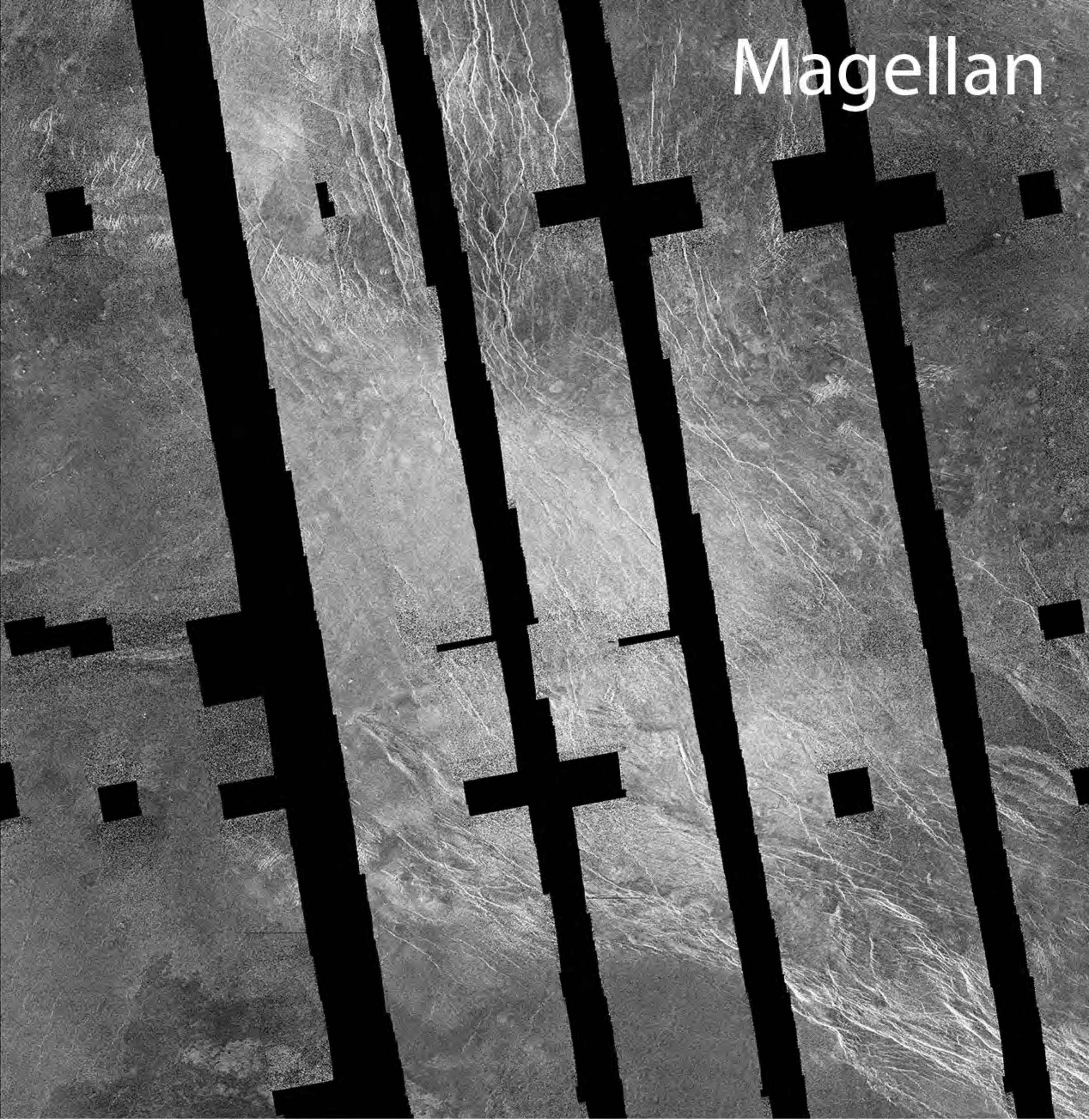




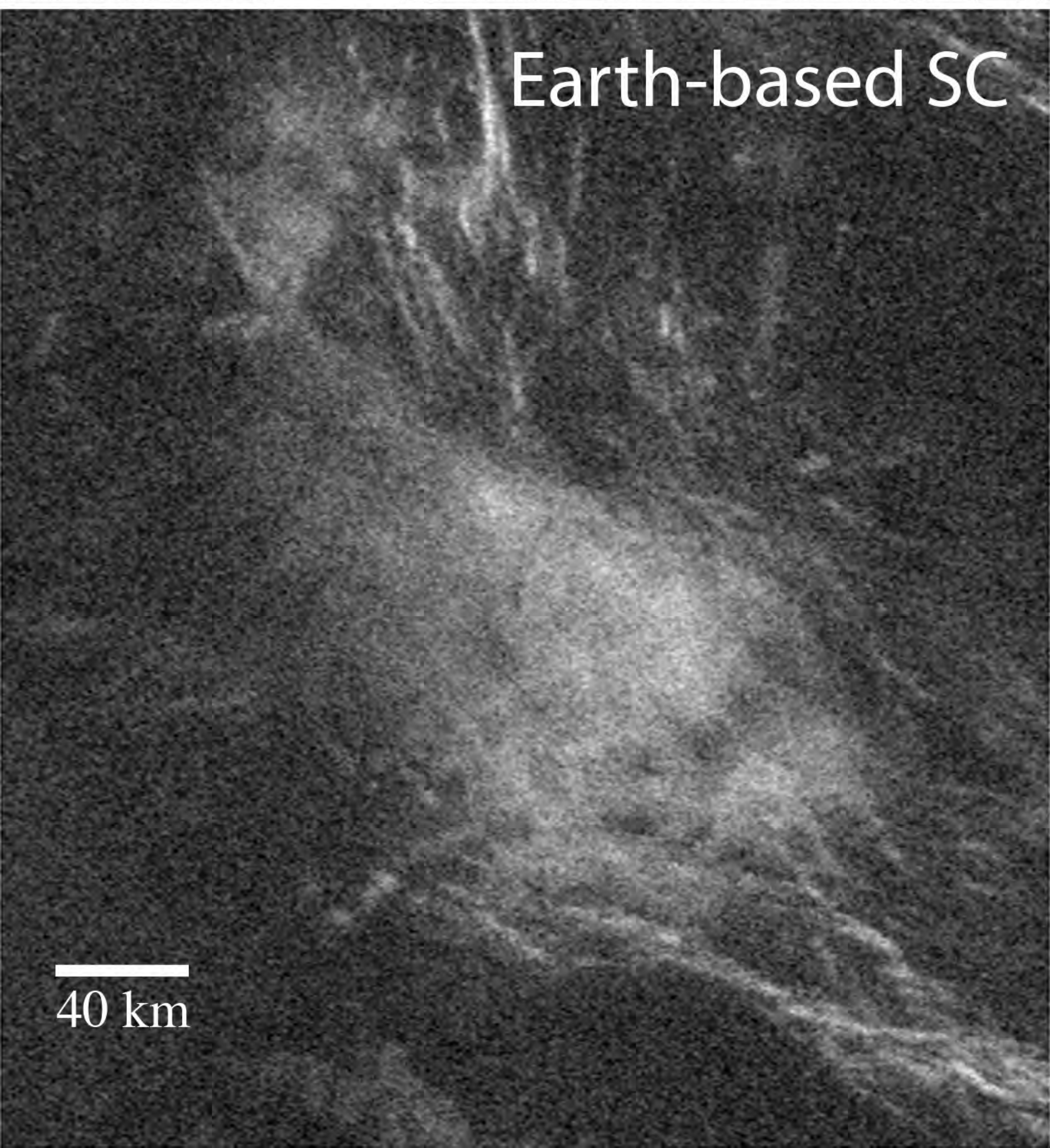
Figure 15.



Magellan



Earth-based SC



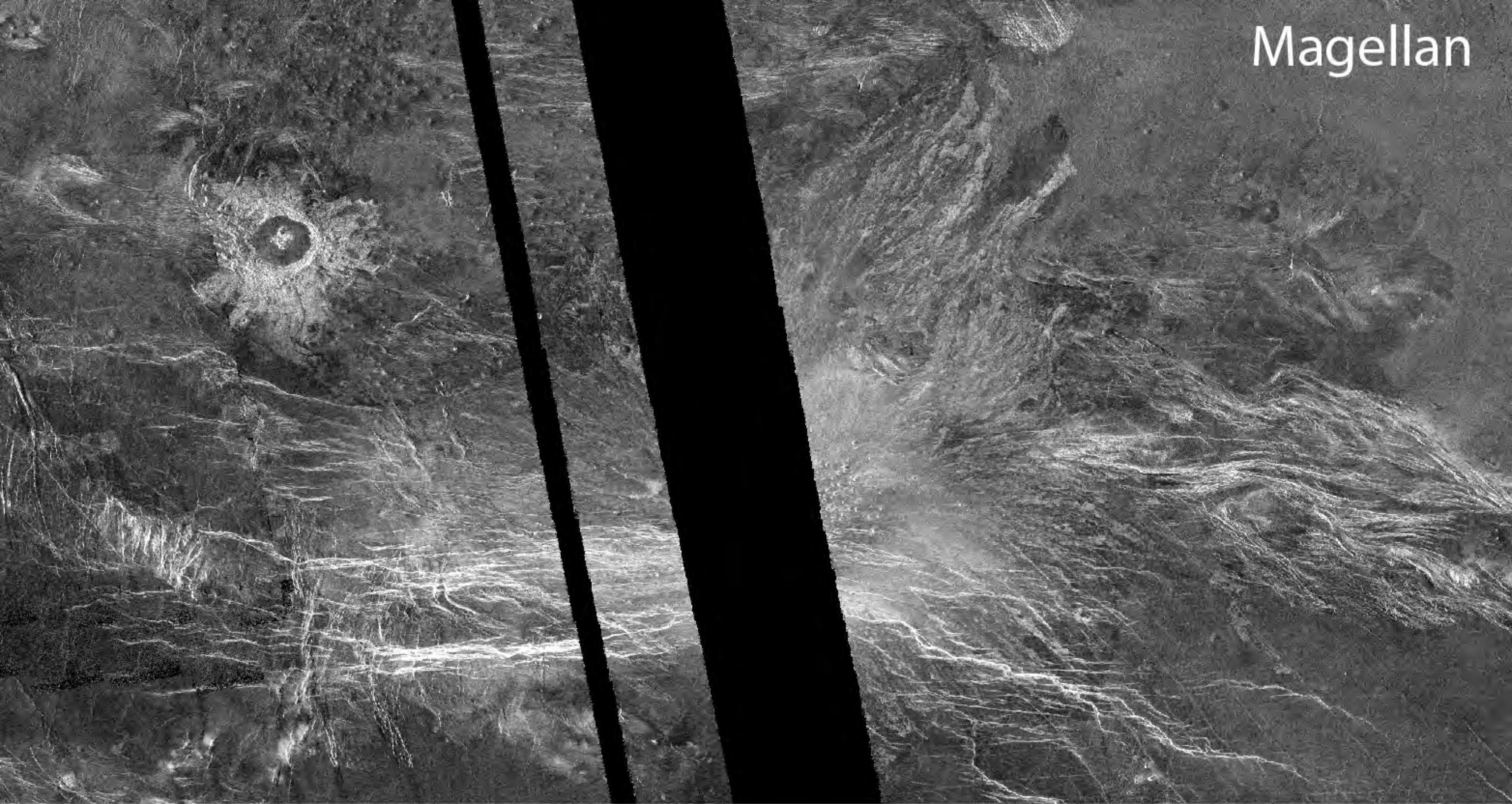
40 km



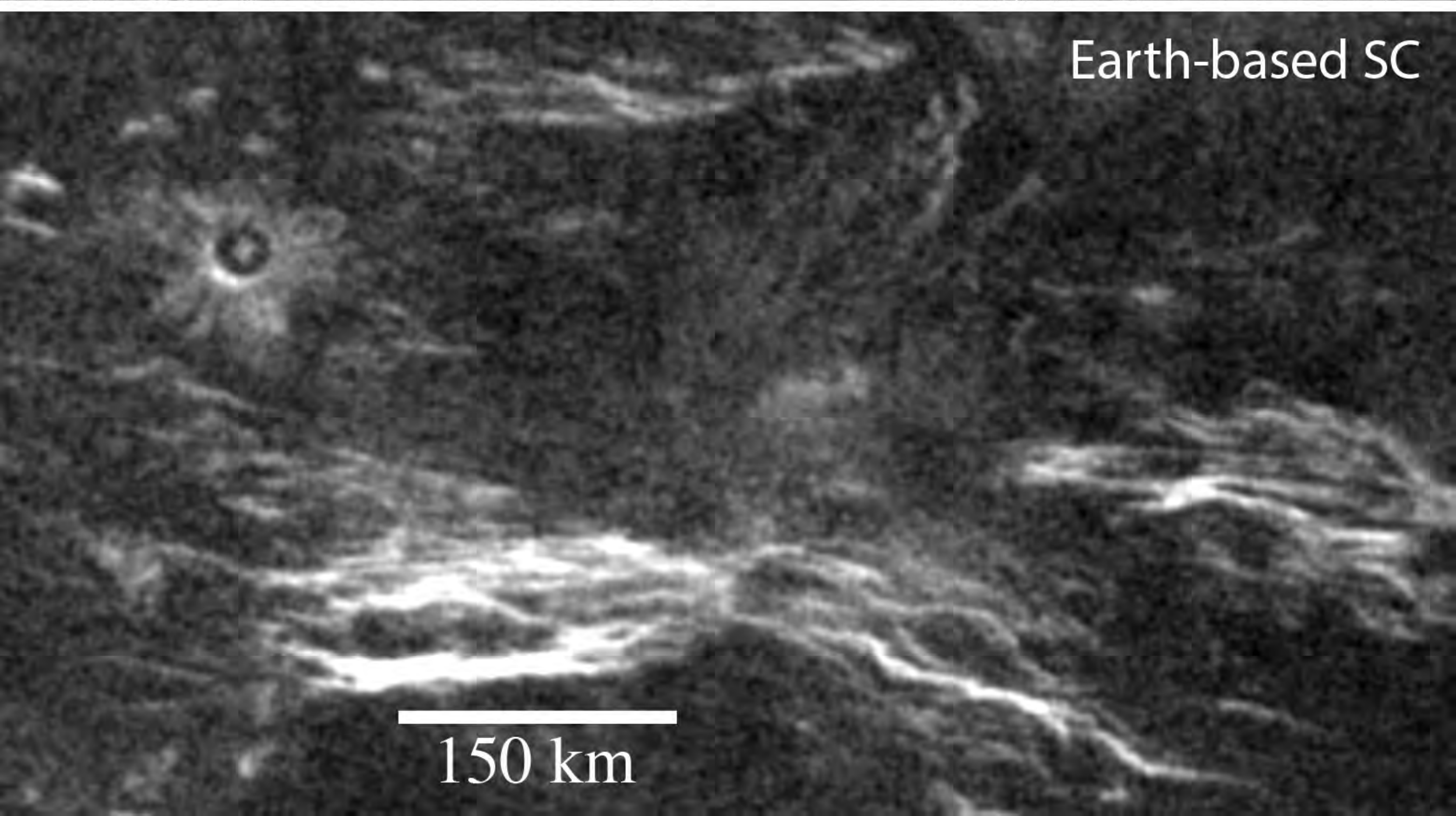
Figure 16.



Magellan



Earth-based SC



150 km



Figure 17.



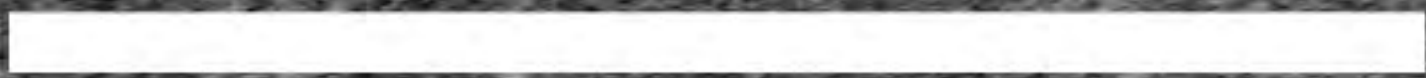
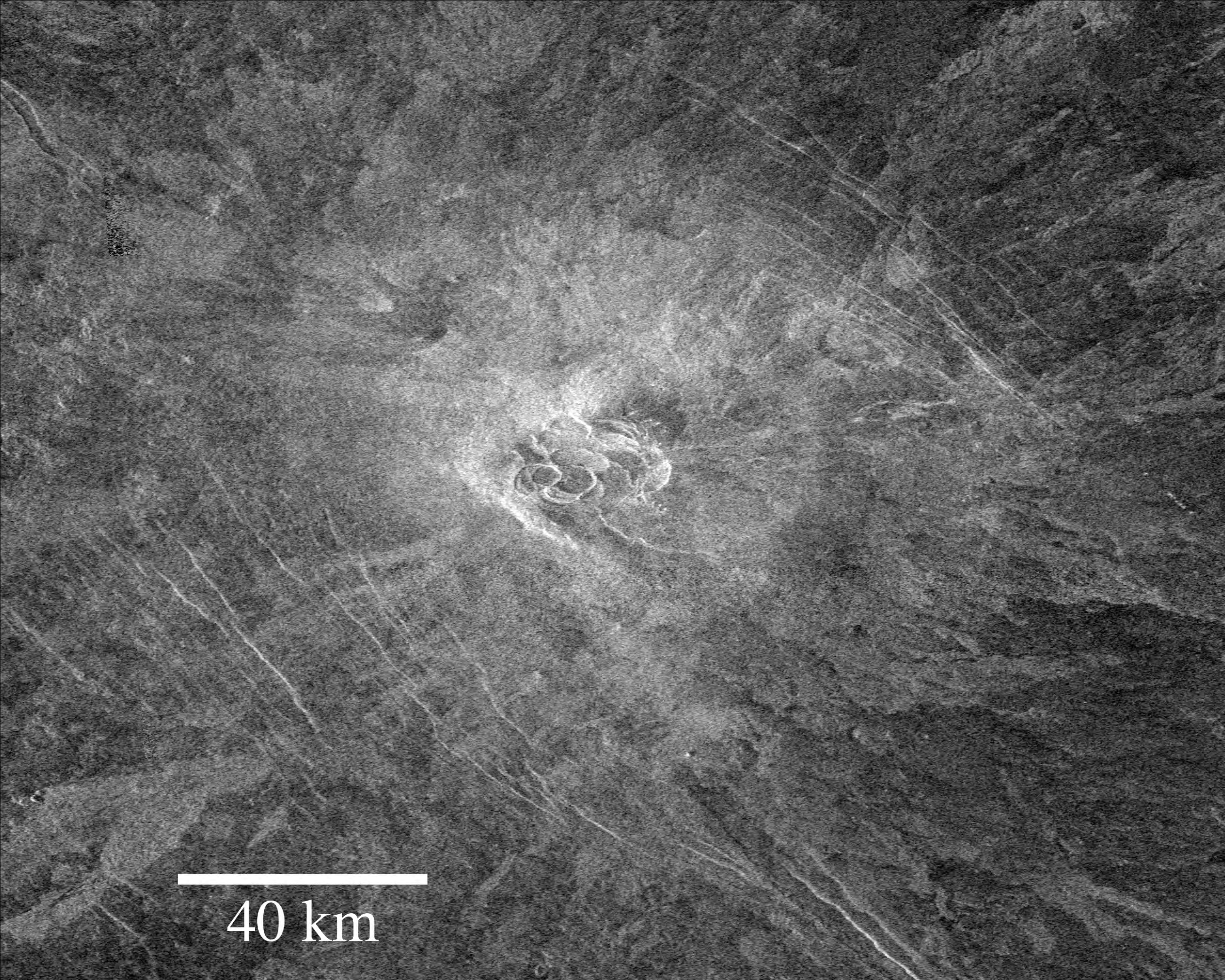
Earth-based SC

80 km



Figure 18.



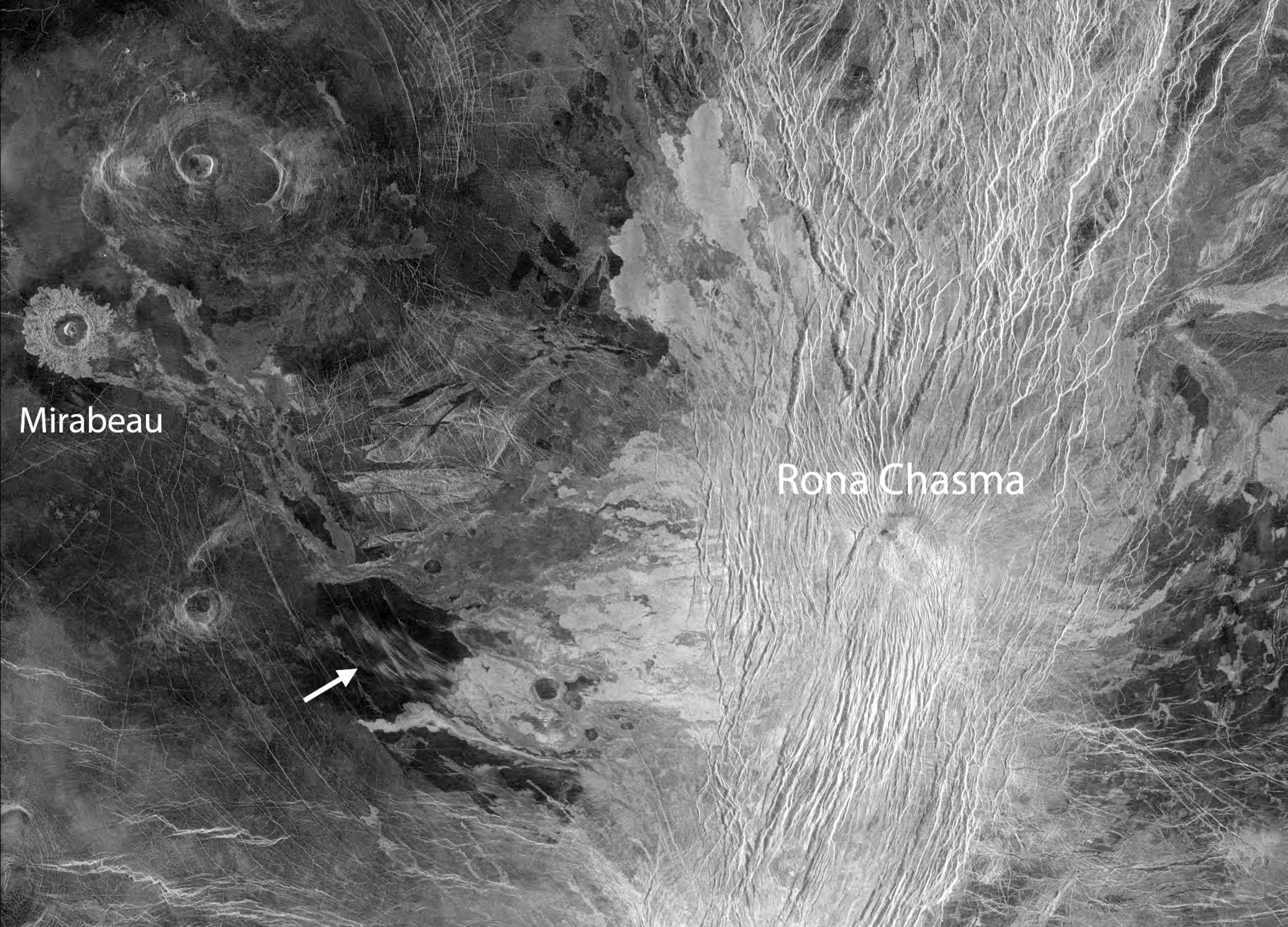


40 km



Figure 19.





Mirabeau

Rona Chasma





Figure 20.





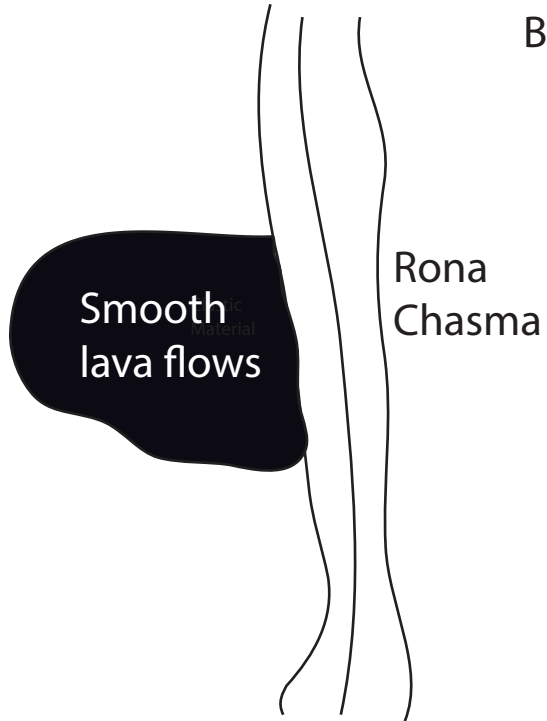
40 km



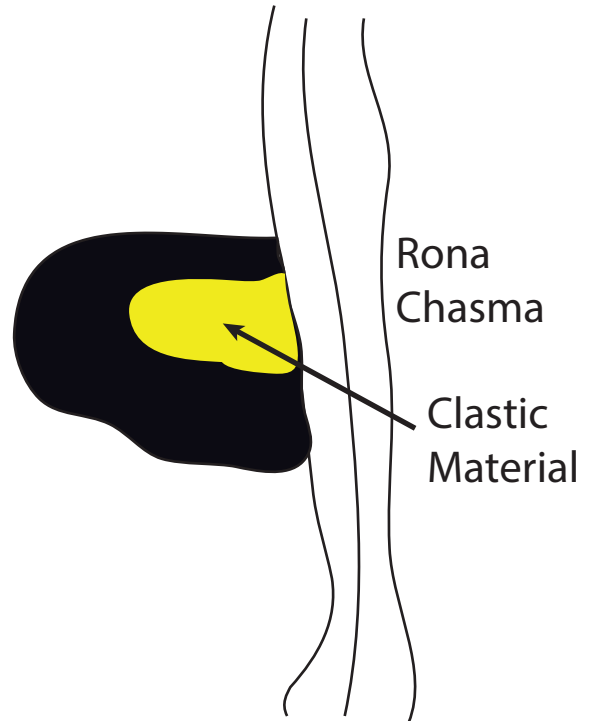
Figure 21.



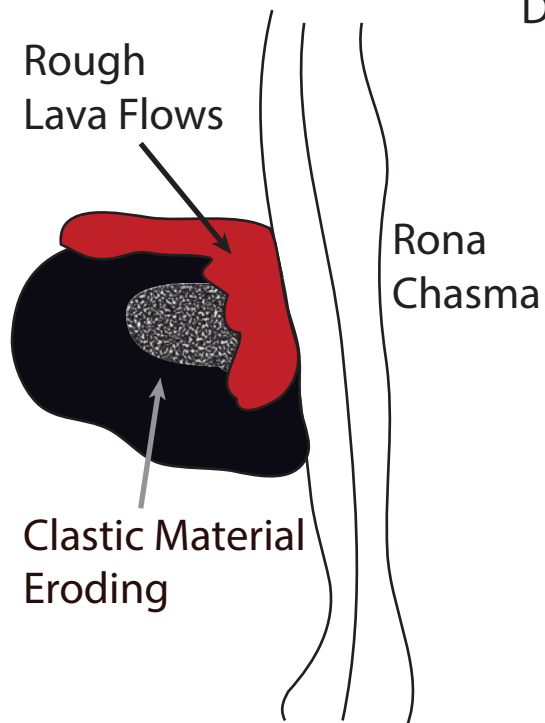
A



B



C



D

